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Performance of Tape-Bonded Seams of EPDM Membranes: Effect of Material and Application Factors on Peel Creep-Rupture Response

Walter J. Rossiter, Jr., Mark G. Vangel, Kevin M. Kraft, and James J. Filliben

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ABSTRACT

An investigation, conducted under the auspices of an industry-government consortium, studied the effects of material and application factors on the peel creep-rupture response and peel strength of EPDM (ethylene-propylene-diene terpolymer) tape-bonded seam specimens. Two material factors (tape system and thickness) and five application factors (EPDM surface condition, primer, application temperature, application pressure, and time-at-application-temperature) were examined in a two-level statistically designed experiment. Some tapes had thicknesses typical of those commercially available at the time of the study, and were designated as having 'standard' thickness. The thicknesses of 'standard' and thin tapes were approximately 0.9 mm (0.035 in) and 0.6 mm (0.025 in), respectively. Specimens were prepared either primed or unprimed using EPDM that was either cleaned or contaminated. Application temperatures were low, 5 °C (41 °F), or high, 60 °C (140 °F), and application pressures were low, 0.2 MPa (30 lbf/in^2), or high, 2 MPa (300 lbf/in^2). The time at which the specimens remained at the application temperature was short, about 24 hours, or long, 672-960 hours. To interpret the data, plots of mean time-to-failure and mean peel strength versus the combinations of application factors for each of the four pairs of tape system and tape thickness were analyzed. Comparisons of times-to-failure between the tape-bonded sample sets were made with those of liquid-adhesive-bonded sample sets tested in an earlier phase of the study. The main conclusions regarding tape-bonded seams from the present investigation are that:

- Primed, clean EPDM provided the longest times-to-failure and highest peel strengths.
- Primed, clean EPDM and 'standard' thickness tape afforded times-to-failure that were statistically significantly higher than minimum mean times-to-failure of well prepared liquid-adhesive-bonded sample sets determined in an earlier investigation.
- The application temperatures and application pressures used in the investigation did not affect the times-to-failure of sample sets prepared with primed, clean EPDM, that had, as stated, relatively long times-to-failure.
- 'Standard' thickness tape provided significantly longer times-to-failure than thinner tape.
- The two tape systems generally responded similarly to factors that promoted either shorter or longer times-to-failure.

Key Words: adhesive tapes; adhesive testing; application factors; building technology; creep-rupture; EPDM membranes; peel strength; roofing; seams; time-to-failure

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1. INTRODUCTION

1.1 Background

An industry-government consortium study has been undertaken to: (1) compare the creep-rupture performance of tape-bonded and liquid-adhesive-bonded seams of EPDM membranes, and (2) recommend a test protocol and criteria for evaluating creep-rupture performance of such seams. In recent years, the use of preformed tapes for fabricating seams of EPDM membranes has increased substantially, and is expected to continue to grow [1]. The consortium study was initiated at the National Institute of Standards and Technology (NIST) in late 1994 in response to industry requests that independent evaluations be conducted and that nonproprietary data be developed on the performance of tape-bonded seams [2].

Three EPDM membrane manufacturers (Carlisle Syntec, Firestone, and GenFlex), and two tape-system manufacturers (Adco and Ashland) along with two trade associations (NRCA and RCI)* joined with NIST through a Cooperative Research and Development Agreement (CRADA) to design and conduct the study. The experimental program consists of three 1-year phases. Phases I and II have been completed and Phase III is ongoing. A summary of the objective of each phase is as follows:

- In Phase I, the creep-rupture response (time-to-failure) of tape-bonded seam specimens subjected to various peel loads under ambient conditions was compared to that of liquid-adhesive-bonded specimens.
- In Phase II, which is the subject of the present report, the peel creep-rupture response and peel strength of tape-bonded seam specimens were investigated under ambient conditions for a number of material and application variables (Section 1.3).
- In Phase III, the creep-rupture response of tape-bonded seam specimens will be investigated as a function of test temperature and type of loading (i.e., peel versus shear).

In the creep-rupture experiments, seam specimens of a fixed length are stressed under a constant load and the time over which they sustain the load until total separation (i.e., the time-to-failure) is recorded. Results from previous NIST studies on liquid-adhesive-bonded specimens have shown that creep-rupture tests provide a sensitive procedure for evaluating the effects of a multiplicity of application and environmental factors including EPDM surface condition, adhesive thickness, temperature, and ozone on the capability of seams to sustain loads over time [3-9]. These results contributed to recommendations on proper field application of seams. The findings from these past studies also gave impetus to the present industry-government consortium study, because the sensitivity of the creep-resistance of tape-bonded seam specimens to factors such as load, EPDM surface condition, use of primer, and tape thickness was not known.

1.2 Phase I Findings

The results of Phase I were published in NIST Building Science Series (BSS) 175, "Performance of Tape-Bonded Seams of EPDM Membranes: Comparison of the Peel Creep-Rupture Response

*The National Roofing Contractors Association (NRCA) and the Roof Consultants Institute (RCI).

of Tape-Bonded and Liquid-Adhesive-Bonded Seams" [3]. In the Phase I study, seam specimens were prepared at room temperature, 23 °C ± 2 °C (73 °F ± 4 °F)*, using two commercial tape systems (i.e., tape and primer) and one commercial liquid adhesive. In all cases, the EPDM rubber was well cleaned and, in the case of the tape-bonded specimens, a primer was applied. Seam specimens were tested for peel strength and for peel creep-rupture resistance (i.e., times-to-failure) under loads ranging from 3.1 N to 24.9 N (0.7 lbf to 5.6 lbf) in increments of 3.1 N (0.7 lbf).

Figure 1 shows a plot of mean time-to-failure versus load for the Phase I experiments [3]. No data points are shown for the 3.1 N (0.7 lbf) load, because no specimen failures have been observed.** As is evident in Figure 1, the tape-bonded sample sets had times-to-failure that were, in most cases, comparable to or greater than those of the liquid-adhesive-bonded sample sets. And, the tape-bonded specimens provided mean time-to-failure results that were reproducible between replicate sets. The liquid-adhesive-bonded sample sets showed considerable variability. For example, at 9.3 N (2.1 lbf), the times-to-failure of the five liquid-adhesive-bonded sample sets ranged from about 7 hours to 500 hours (fig. 1). In contrast, their mean peel strengths ranged from only 1.87 kN/m to 1.94 kN/m (10.3 lbf/in to 11.1 lbf/in) [3]. That is, although there was wide variability in the times-to-failure, the variability in the peel strengths was small. This finding supports the thesis that creep-rupture tests are more sensitive than peel-strength tests for evaluating factors affecting the capability of seam specimens to support loads over time [3-9].

1.3 Objective and Scope of Phase II

This report presents the results of the Phase II research to investigate the effects of material and application factors on the peel creep-rupture response and peel strength of tape-bonded seam specimens. The specimens were prepared under a variety of conditions according to a predetermined statistical design. A description of the seven factors—tape system, tape thickness, EPDM surface condition, primer, application temperature, application pressure, and time-at-temperature—varied during specimen preparation is given in Table 1 with a comment as to why each factor was included. The peel strengths of the specimens were measured, and times-to-failure were determined under a peel load of 9.3 N (2.1 lbf). The data were statistically analyzed to determine the effects of each factor (Table 1), or interactions between them, on time-to-failure and peel strength.

The Phase II research is an extension of that conducted in Phase I. In Phase I [3], the specimens were 'well prepared' in the laboratory in that the EPDM was always cleaned and primed (in the case of tapes), and the application temperature and application pressure were selected to be in the range that may be experienced in the field (Table 1). The Phase II research addressed the assumption that these material and application factors are variable in practice, and changes in the level of these factors may affect seam time-to-failure and peel strength. For example, in practice, more than one tape system is available, and the tapes can be manufactured with different

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*Temperature variations are absolute bounds.

**Tests at the 3.1 N (0.7 lbf) load are ongoing and, as of this writing, after over 16,800 hours (about 23 months), no specimen failures have been observed.

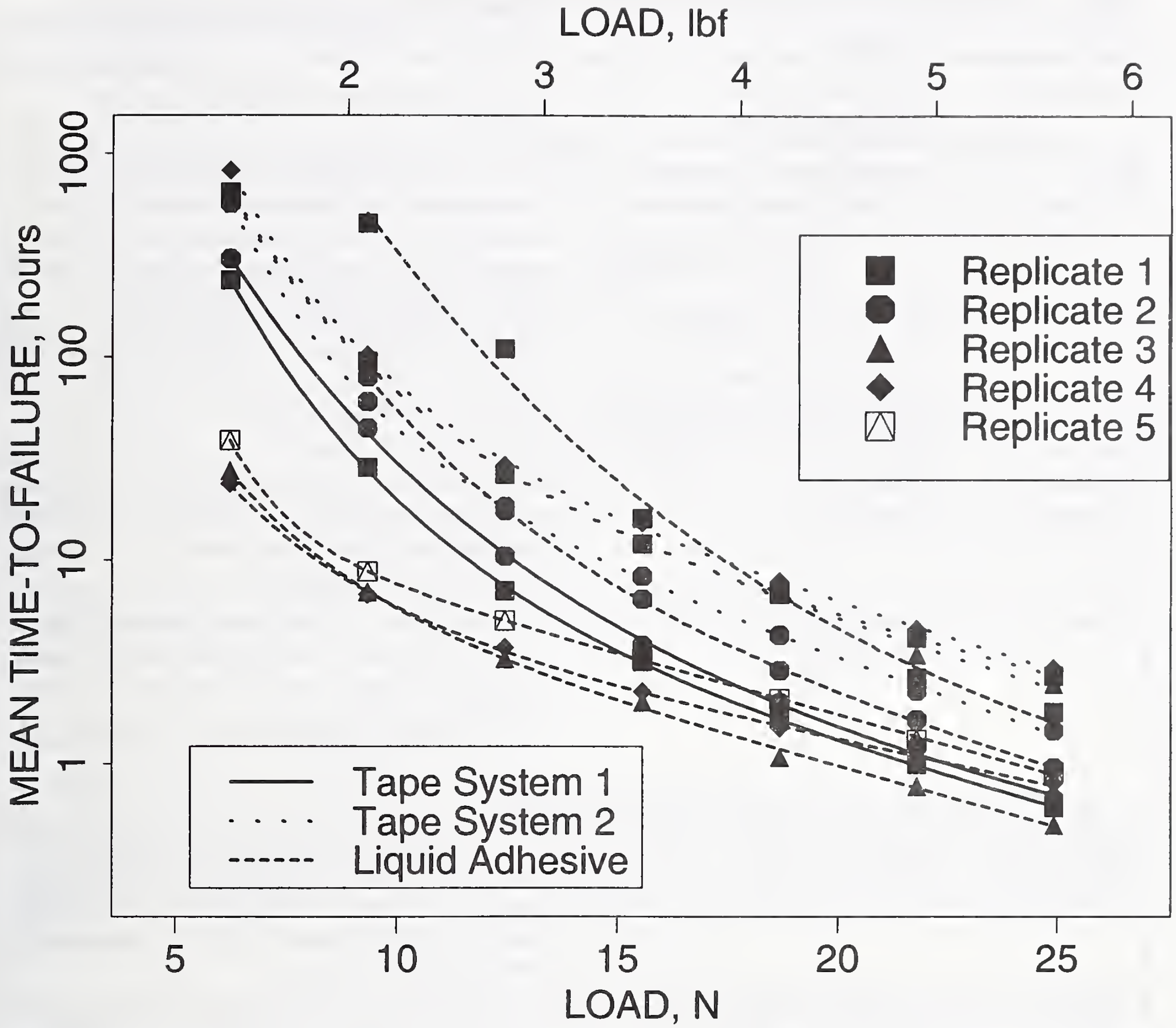

Figure 1. Mean Time-to-Failure Versus Load for the Tape-Bonded and Liquid-Adhesive-Bonded Specimens Investigated in Phase I [3].

thicknesses. Moreover, it is reasonable to assume that cleaning and priming the EPDM might not be carried out in the field as recommended by manufacturers. Also, typical field temperatures at which seams are fabricated may vary from 0 °C (32 °F) or colder to 60 °C (140 °F) or hotter, and pressures applied by roofing mechanics are variable due to the human element associated with manual labor, e.g., strength. Phase II was designed to quantify the effects of these factors.

Additionally, consistent with the overall objective of the research program, the creep-rupture behavior of tape-bonded sample sets prepared under a variety of conditions are compared with that of well prepared liquid-adhesive-bonded sample sets. In recent years, field experience with liquid-adhesive-bonded seams has been, in most cases, satisfactory. Consequently, the laboratory-measured times-to-failure of well prepared liquid-adhesive-bonded specimens were taken as the benchmark for acceptable creep lifetimes.

Table 1. Material and application factors varied during preparation of Phase II specimens

Factor	Description	Comment
Tape System	• Tape System 1 (TS1) • Tape System 2 (TS2)	In practice, tapes are available from a number of suppliers.
Tape Thickness	• Thin: about 0.5 mm to 0.6 mm (0.020 in to 0.025 in) • 'Standard': about 0.9 mm to 1.0 mm (0.035 in to 0.040 in) Note: The thicker tapes had thicknesses typical of those commercially available at the time of the study; thus, they were designated as having 'standard' thickness.	In practice, as manufactured products, tapes may be produced in a variety of thicknesses. Today's tapes generally have thickness of about 0.9 mm (0.035 in). It was of interest to quantify the effect of tape thickness on time-to-failure and compare the results to those previously obtained on liquid-adhesive-bonded specimens. In the latter case, thin layers of adhesive had significantly reduced times-to-failure in comparison to thick layers of adhesive [4-6].[a]
EPDM Surface Condition	• Clean • Contaminated	In practice, proper application of seams requires that the surface of the EPDM sheet be well cleaned. The degree of cleaning can be variable in the field. Lack of cleaning may result in unacceptable seams.
Primer	• Primed EPDM • Unprimed EPDM	In practice, proper application of tape-bonded seams requires that the surface of the EPDM sheet be primed. Nevertheless, it may be assumed that, due to the human element involved, primer may be omitted for some reason; e.g., roofing crew arrives at the job site without primer. Lack of priming may result in unacceptable seams.
Application Temperature	• Low: 5 °C (41 °F) • High: 60 °C (140 °F)	In practice, seams may be fabricated with membrane materials at temperatures ranging from 0 °C (32 °F) or colder to 60 °C (140 °F) or higher. The selected range simulates hot and cold temperatures that are routinely experienced in the field.[b]
Application Pressure	• Low: 0.2 MPa (30 lbf/in^2) • High: 2 MPa (300 lbf/in^2)	In practice, seams may be fabricated over a range of pressures depending on the roofing mechanic. Strong [10] has reported that normal application pressures exerted by roofing mechanics are about 0.7 MPa (100 lbf/in^2). The range selected for study brackets that pressure by a factor of about three.
Time-at-Temperature[c]	• Short: 20 h to 24 h at the application temperature, then stored at room temperature until tested • Long: stored at application temperature until tested, about 672 h to 960 h	In practice, seams may remain for relatively long periods of time at the temperature at which they were fabricated. On the other hand, under some circumstances, the temperature may change shortly after seam preparation.

[a]Field experience with tapes available when the experiment was designed provided no reason for including tape thicknesses greater than 'standard.'

[b]Temperatures below 0 °C (32 °F) and above 60 °C (140 °F) are encountered in practice. However, practical constraints associated with preparing laboratory specimens below 0 °C (32 °F) and above 60 °C (140 °F) precluded investigating the effects of such temperature extremes.

[c] "Time-at-temperature" refers to holding the completed specimen at the preparation temperature for a specified duration.

2. EXPERIMENTAL DESIGN

2.1 Factors

The seven factors detailed in Table 1 were selected for study* by the consortium steering committee members. These factors can be classified into two material factors (tape system and tape thickness) and five application factors (EPDM surface condition, primer, application temperature, application pressure, and time-at-temperature). Whenever possible, the user would like to select a combination of levels of these application factors which would consistently produce good-quality seams whatever the values of the material factors. Of the material factors, the user may, or may not, have the possibility of selecting the tape system and tape thickness.

A naive approach to experimentation would vary each of the seven factors individually, leaving all but one factor set at 'typical' values for each experiment. This form of experimentation is highly inefficient, since it provides no information on potential factors which might prove important in combination with one another: for example, high pressure might be desirable at low temperatures, but low pressure might be better at high temperatures. When the effect of a factor on a response depends on the level of other factors, these factors are said to interact. 'One factor at a time' experimentation provides no information about potential interactions, since the factors are never varied simultaneously.

2.2 Sample Size and Levels for Factors

Available experimental resources such as time for testing, test chambers, and raw materials suggested that it would not be possible to test more than about 500 specimens. For example, once a creep chamber was committed to testing, it ought not to be disturbed until all specimens had failed. Such constraints made it necessary to design a single large experiment (including a pilot study) rather than a series of smaller experiments.

From Phase I experience with the creep-rupture tests [3], it appeared that eight specimens for each combination of factor levels would be adequate. For simplicity, it was decided to consider only two levels of each of the seven factors, and to choose these levels far enough apart so that the range of practical importance was generally covered (Table 1).

2.3 Pilot Study to Determine Creep Load

Phase I produced extensive data on times-to-failure and peel strength at various loads (fig. 1), so it was decided to perform the present investigation at a single load. Implicit in this decision is the assumption that the experimentalist would be willing to ignore any interaction of load with the other factors under consideration.

A pilot study was performed to select a single load. Eight sample sets, each having eight specimens, were subjected to creep-rupture testing at each of four loads: 9.3 N, 12.5 N, 15.6 N, and 18.7 N (2.1 lbf, 2.8 lbf, 3.5 lbf, and 4.2 lbf). Four of these sample sets were 'poorly prepared' (unprimed, contaminated EPDM surface, and 0.2 MPa/30 lbf/in^2 application pressure),

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*Referred to herein as the Phase II Main Experiment.

whereas the remaining four were 'well prepared' (primed, clean EPDM surface, and 2 MPa/300 lbf/in^2 application pressure). On the basis of this pilot study, it was considered that a load of 9.3 N (2.1 lbf) would likely result in a creep experiment which could be completed within a reasonable time; that is, specimens would fail soon enough to obtain results within a few weeks or less, but not so quickly as to obscure relevant distinctions among the sample sets.

2.4 Fractional Factorial Design

The primary objective of the Phase II Main Experiment was to determine which factors and interactions are most important, as measured by the effect that varying these factors had on creep life and peel strength. As discussed in Section 2.1, it is necessary to vary factors together in order to estimate interactions. A statistical design which required testing at all combinations of levels for all factors is called a (full) factorial design. Usually two levels are chosen for each factor, since such a design is relatively easy to analyze, and since more levels can require considerably more testing. It is also desirable that, where appropriate, levels of factors be set at the extremes of what is likely to be observed in practice.

When the amount of testing required for a full factorial experiment (even with only two levels per factor) is prohibitive, a carefully chosen fraction of all possible combinations is usually selected at the cost of not being able to assess separately all of the interactions and possibly, also, certain main effects. Such a design, called a fractional factorial, was used in this study.

There are $2^7 = 128$ possible combinations of the seven factors (each at one of two levels) given in Table 1. Eight specimens for each of these 128 combinations would require 1024 specimens for the full experiment. This was too many by about a factor of two, so a half-fraction of the full factorial design was chosen. This design included the four combinations of material factors (Table 2), and 16 of the 32 possible combinations of the application factors (Table 3). The same 16 combinations of the application factors were assigned to each of four combinations of the material factors. Since the user of a tape system may have little or no ability to control the material factors, it was concluded that this design would lead to the selection of combinations of levels of application factors which produced 'good' seams, as quantified by time-to-failure and peel strength, for *all* combinations of material factors.

Table 2. Combinations of material factors selected in the experimental design

Tape System No.	Tape Thickness
TS1	Thin
TS1	'Standard'
TS2	Thin
TS2	'Standard'

Table 3. Combinations of application factors selected in the experimental design[a]

EPDM Surface Condition	Primer	Application Temperature	Application Pressure	Time-at-Temperature
Contaminated	Primed	High	High	Short
Contaminated	Unprimed	Low	High	Short
Contaminated	Unprimed	High	Low	Short
Contaminated	Primed	Low	Low	Short
Clean	Unprimed	High	High	Short
Clean	Primed	Low	High	Short
Clean	Primed	High	Low	Short
Clean	Unprimed	Low	Low	Short
Contaminated	Primed	High	High	Long
Contaminated	Unprimed	Low	High	Long
Contaminated	Unprimed	High	Low	Long
Contaminated	Primed	Low	Low	Long
Clean	Unprimed	High	High	Long
Clean	Primed	Low	High	Long
Clean	Primed	High	Low	Long
Clean	Unprimed	Low	Low	Long

[a]See Table 1 for description of the factors.

The resultant design provided 64 sample sets (four for each combination of material factors times 16 for each combination of application factors) divided equally between the two tape systems. Tables 4A and 4B describe the 32 sample sets for Tape System 1 and the 32 sample sets for Tape System 2, respectively.

Table 4A. Description of the Tape System 1 sample sets

	Material Factors		Application Factors				
Sample Set No.	Tape Thickness	Tape System	EPDM Surface Condition	Primer	Application Temperature	Application Pressure	Time-at-Temperature
1	Thin	1	Contaminated	Primed	High	Low	Short
2	Thin	1	Contaminated	Unprimed	Low	High	Short
3	Thin	1	Contaminated	Unprimed	High	Low	Short
4	Thin	1	Contaminated	Primed	Low	High	Short
5	Thin	1	Clean	Unprimed	High	Low	Short
6	Thin	1	Clean	Primed	Low	High	Short
7	Thin	1	Clean	Primed	High	Low	Short
8	Thin	1	Clean	Unprimed	Low	High	Short
9	Standard	1	Contaminated	Primed	High	Low	Short
10	Standard	1	Contaminated	Unprimed	Low	High	Short
11	Standard	1	Contaminated	Unprimed	High	Low	Short
12	Standard	1	Contaminated	Primed	Low	High	Short
13	Standard	1	Clean	Unprimed	High	Low	Short
14	Standard	1	Clean	Primed	Low	High	Short
15	Standard	1	Clean	Primed	High	Low	Short
16	Standard	1	Clean	Unprimed	Low	High	Short
33	Thin	1	Contaminated	Primed	High	Low	Long
34	Thin	1	Contaminated	Unprimed	Low	High	Long
35	Thin	1	Contaminated	Unprimed	High	Low	Long
36	Thin	1	Contaminated	Primed	Low	High	Long
37	Thin	1	Clean	Unprimed	High	Low	Long
38	Thin	1	Clean	Primed	Low	High	Long
39	Thin	1	Clean	Primed	High	Low	Long
40	Thin	1	Clean	Unprimed	Low	High	Long
41	Standard	1	Contaminated	Primed	High	Low	Long
42	Standard	1	Contaminated	Unprimed	Low	High	Long
43	Standard	1	Contaminated	Unprimed	High	Low	Long
44	Standard	1	Contaminated	Primed	Low	High	Long
45	Standard	1	Clean	Unprimed	High	Low	Long
46	Standard	1	Clean	Primed	Low	High	Long
47	Standard	1	Clean	Primed	High	Low	Long
48	Standard	1	Clean	Unprimed	Low	High	Long

Table 4B. Description of the Tape System 2 sample sets

	Material Factors		Application Factors				
Sample Set No.	Tape Thickness	Tape System	EPDM Surface Condition	Primer	Application Temperature	Application Pressure	Time-at-Temperature
17	Thin	2	Contaminated	Primed	High	Low	Short
18	Thin	2	Contaminated	Unprimed	Low	High	Short
19	Thin	2	Contaminated	Unprimed	High	Low	Short
20	Thin	2	Contaminated	Primed	Low	High	Short
21	Thin	2	Clean	Unprimed	High	Low	Short
22	Thin	2	Clean	Primed	Low	High	Short
23	Thin	2	Clean	Primed	High	Low	Short
24	Thin	2	Clean	Unprimed	Low	High	Short
25	Standard	2	Contaminated	Primed	High	Low	Short
26	Standard	2	Contaminated	Unprimed	Low	High	Short
27	Standard	2	Contaminated	Unprimed	High	Low	Short
28	Standard	2	Contaminated	Primed	Low	High	Short
29	Standard	2	Clean	Unprimed	High	Low	Short
30	Standard	2	Clean	Primed	Low	High	Short
31	Standard	2	Clean	Primed	High	Low	Short
32	Standard	2	Clean	Unprimed	Low	High	Short
49	Thin	2	Contaminated	Primed	High	Low	Long
50	Thin	2	Contaminated	Unprimed	Low	High	Long
51	Thin	2	Contaminated	Unprimed	High	Low	Long
52	Thin	2	Contaminated	Primed	Low	High	Long
53	Thin	2	Clean	Unprimed	High	Low	Long
54	Thin	2	Clean	Primed	Low	High	Long
55	Thin	2	Clean	Primed	High	Low	Long
56	Thin	2	Clean	Unprimed	Low	High	Long
57	Standard	2	Contaminated	Primed	High	Low	Long
58	Standard	2	Contaminated	Unprimed	Low	High	Long
59	Standard	2	Contaminated	Unprimed	High	Low	Long
60	Standard	2	Contaminated	Primed	Low	High	Long
61	Standard	2	Clean	Unprimed	High	Low	Long
62	Standard	2	Clean	Primed	Low	High	Long
63	Standard	2	Clean	Primed	High	Low	Long
64	Standard	2	Clean	Unprimed	Low	High	Long

3. SPECIMEN PREPARATION AND TESTING

3.1 Materials

Two tape systems, comprised of a preformed tape and primer and designated Tape System 1 (TS1) and Tape System 2 (TS2), were used to prepare the specimens. Both the TS1 and TS2 tapes, and also the TS2 primer, were obtained at the beginning of the Phase II studies.* The TS1 primer was that previously used during the Phase I studies. The EPDM sheet was a commercial product having a thickness of about 1.5 mm (0.060 in). Appendix A presents the experimental details on specimen preparation under the various conditions listed in Table 1. The experimental design included TS1 and TS2 tapes that were commercial products at the time of the study. These commercial tapes were designated as having 'standard' thickness, which is the term used in this present report for the thicker tapes. The 'thin' tapes were noncommercial products made specifically for the Phase II investigations.

3.2 Creep-Rupture Tests

Eight peel specimens, randomly selected from each sample set, were subjected to creep-rupture testing under the 9.3 N (2.1 lbf) load. The tests were conducted at room temperature, 23 °C ± 2 °C (73 °F ± 4 °F), in laboratory-constructed chambers according to the general procedure described in Martin, Embree, Stutzman, and Lechner [5]. The chambers were designed to load the specimens simultaneously. The relative humidity in the chambers was maintained between 40 % and 45 % using a saturated potassium carbonate solution [11]. Built-in fans circulated the air in the chambers. The relative humidity in each chamber was checked using a Labcraft Digital Hygrometer, Model Number 244-354.** Specimens were conditioned for a minimum of 16 hours in the chambers before applying the creep load. The times-to-failure (i.e., time under load until the two EPDM strips comprising the specimens completely separated) were recorded (± 1 s) electronically for each specimen using a computerized monitoring and data-logging system.

3.3 Peel-Strength Tests

Four T-peel specimens were randomly selected from each sample set, and the T-peel strengths were determined at room temperature, 23 °C ± 2 °C (73 °F ± 4 °F), at a crosshead rate of 50 mm/min (2 in/min). The universal testing machine was equipped with hardware and software for recording and calculating peel-strength data. After testing, each specimen was visually examined and the mode of failure, adhesive or cohesive, was noted.

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*The TS1 tapes arrived in two shipments; whereas the TS2 tapes came in one shipment.

**Certain company products are mentioned by name in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment is necessarily the best available for the purpose.

3.4 Measurement of Tape Modulus

Tensile modulus of the tapes was determined at room temperature using the universal testing machine at a crosshead rate of 500 mm/min (20 in/min). Dumbbell-shaped specimens, having a total length of 75 mm (3 in) with a reduced section length of 25 mm (1 in) and width of 3.2 mm (⅛ in) were cut from the tape-roll material using a die and press. Before cutting, the tape was covered with talc to prevent sticking to the die.

4. RESULTS AND DISCUSSION

4.1 Statistical Analysis

To analyze the Phase II Main Experiment results, the plots in Figures 2 and 3 were prepared as summaries of the time-to-failure and peel-strength data, respectively. Note that the time-to-failure axis is logarithmic, while the peel strength axis is linear. The plots are means (either time-to-failure or peel strength) for each of the 16 combinations of application factors. The plot characters (along with the figure legends) identify the combinations of the tape system and tape thickness (i.e., the material factors). The horizontal axis specifies the levels of the five application factors. The application factor combinations are ordered in increasing mean response. The mean for the four sample sets (i.e., TS1-thin, TS1-'standard', TS2-thin, and TS2-'standard') prepared at each combination of application factors is indicated by the dotted line.

Formal statistical analyses including analysis of variance and multiple comparisons provided quantitative support for the discussions that follow (Sections 4.2 and 4.3). However, because the discussions of Figures 2 and 3 adequately describe the results of the study, a complex presentation of the formal analyses is omitted.

In addition to the creep-rupture data developed in Phase II, Figure 2 also contains a horizontal dashed line. It represents the average time-to failure for the three sets of well prepared liquid-adhesive-bonded specimens (i.e., those fabricated with industry-recommended adhesive thickness and clean EPDM) that had the lowest average times-to-failure at 9.3 N (2.1 lbf) in Phase I (fig. 1). The dashed line is included to provide a point of comparison between the Phase II data for tape-bonded sample sets and liquid-adhesive-bonded sample sets (Section 4.2.2). The lowest mean times-to-failure for the liquid-adhesive-bonded sample sets were selected for comparison, because sets with these mean times-to-failure are considered representative of the minimum of the range of liquid-adhesive-bonded seams typically used in current practice. That is, the question addressed is whether tape-bonded sample sets prepared under a variety of conditions perform equal to, or better than, the lowest mean performance of well prepared liquid-adhesive-bonded sample sets.

4.2 Discussion of Creep-Rupture Data

The results of the creep-rupture tests as a function of material and application factors are summarized in Tables 5A and 5B for the 32 TS1 and 32 TS2 sample sets, respectively. Appendix B gives the time-to-failure and failure mode for each specimen along with the thickness of the tape. As shown in the Tables 5A and 5B, the majority (about 80 %) of the coefficients of variation (CoV) for the mean times-to-failure were greater than 20 %. This was in contrast to the results of the Phase I study [3] wherein about 75 % of the coefficients of variation were less than 20 percent. It seems likely that the increased data scatter in the present study could be attributed to increased nonuniformity between specimens in a set because of preparation under application conditions that are more difficult to control than those in Phase I (e.g., high and low temperatures versus room temperatures).

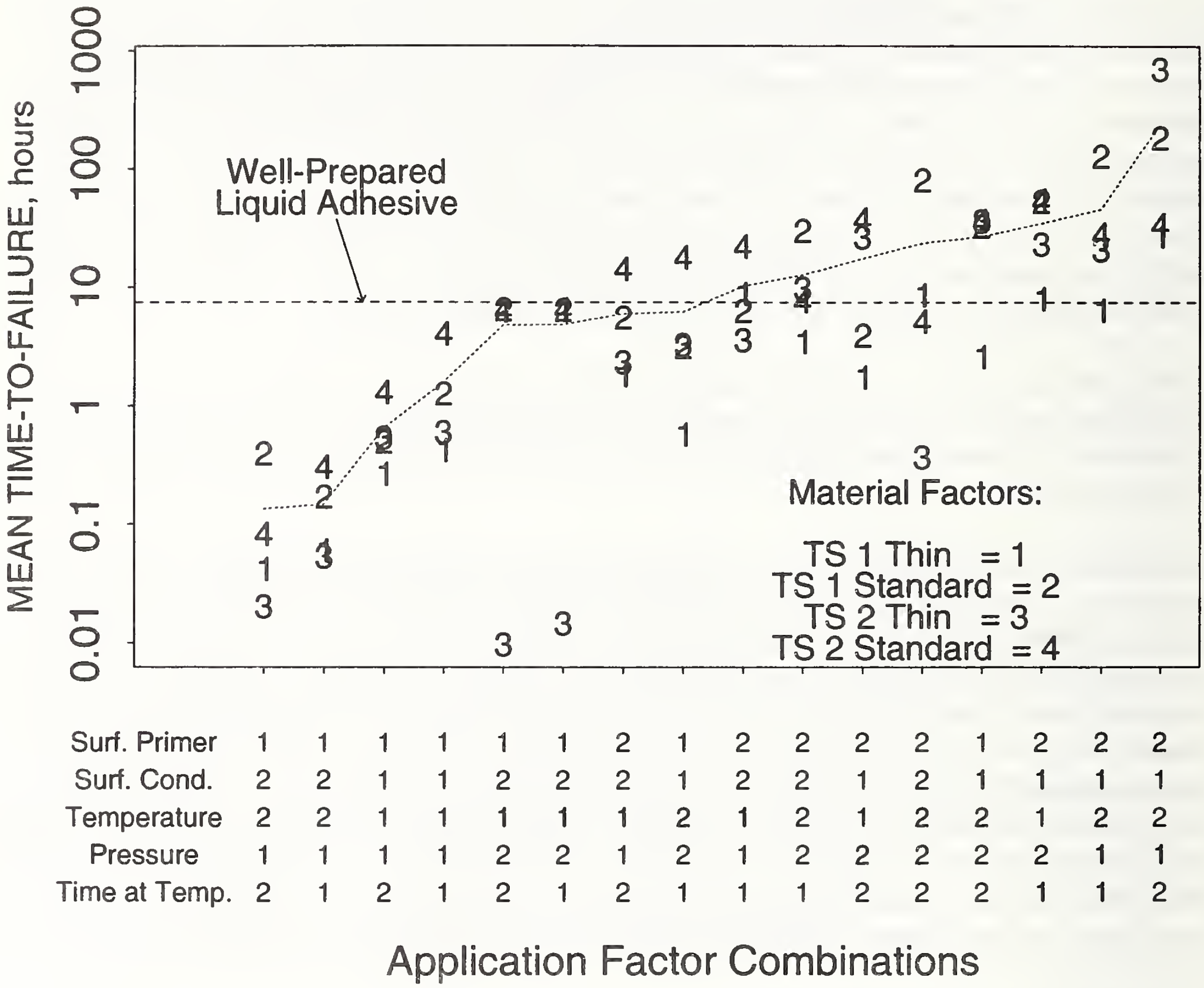
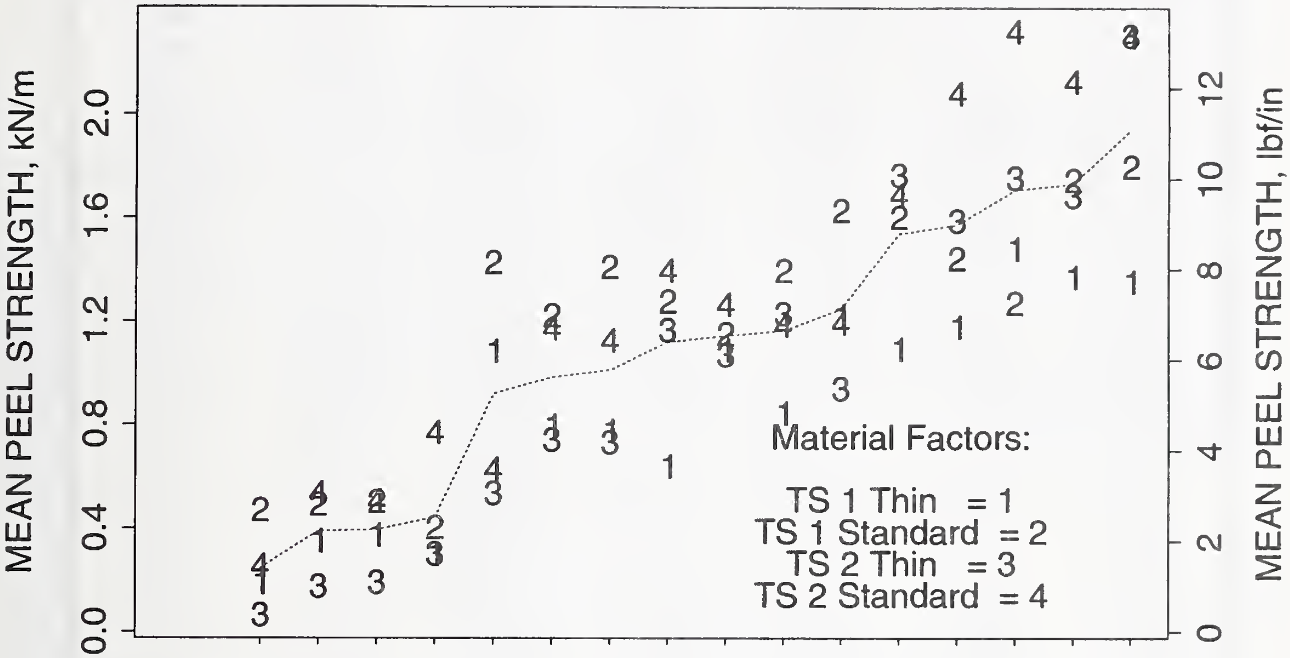


Figure 2. Mean Time-to-Failure in Hours Versus Combinations of Application Factors. (Primer: Unprimed = 1, Primed = 2; EPDM Surface Condition: Clean = 1, Contaminated = 2; Application Temperature: Low = 1, High = 2; Application Pressure: Low = 1, High = 2; Time-at-Temperature: Short = 1, Long = 2.) The horizontal dashed line represents the mean time-to-failure of the three sets of well prepared, liquid-adhesive-bonded specimens (i.e., those fabricated with industry-recommended adhesive thickness and clean EPDM) that had the lowest mean times-to-failure at the 9.3 N (2.1 lbf) load in Phase I (see fig. 1). The dotted line represents the mean for the four sample sets of tape-bonded specimens prepared at each combination of application factors.



Surf. Primer	1	1	1	1	2	2	2	1	1	1	2	1	2	2	2	2
Surf. Cond.	2	2	2	2	2	2	2	1	1	1	2	1	1	1	1	1
Temperature	2	1	1	2	2	1	1	1	1	2	2	2	1	1	2	2
Pressure	1	2	2	1	2	1	1	1	1	2	2	2	2	2	1	1
Time at Temp.	2	2	1	1	2	1	2	1	2	1	1	2	2	1	1	2

Application Factor Combinations

Figure 3. Mean Peel Strength Versus the Combinations of Application Factors. (Primer: Unprimed = 1, Primed = 2; EPDM Surface Condition: Clean = 1, Contaminated = 2; Application Temperature: Low = 1, High = 2; Application Pressure: Low = 1, High = 2; Time-at-Temperature: Short = 1, Long = 2.) The dotted line represents the mean for the four sample sets of tape-bonded specimens prepared at each combination of application factors.)

Table 5A. Summary of the T-peel creep-rupture data for Tape System 1

Sample Set No.	Time-to-Failure, hours min	max	mean	sd[a]	CoV[b] %	Failure Mode[c]
1	1.74	4.95	3.46	1.26	36.5	3(8)
2	6.37	6.39	6.38	0.01	0.1	2(8)
3	0.05	0.07	0.06	0.01	13.5	2(8)
4	7.35	11.96	8.84	1.49	16.8	2(8)
5	0.39	0.99	0.57	0.20	34.2	2(8)
6	2.76	11.24	8.02	3.36	41.9	1(2), 2(1), 3(5)
7	4.00	9.94	6.38	2.12	33.2	2(6), 3(2)
8	0.29	0.63	0.42	0.12	28.2	2(8)
9	10.99	46.28	30.26	11.81	39.0	1(6), 3(2)
10	6.42	6.52	6.47	0.03	0.5	2(8)
11	0.08	0.24	0.17	0.06	32.9	2(8)
12	4.02	9.47	6.37	2.02	31.7	2(8)
13	1.74	5.97	3.17	1.26	39.9	2(8)
14	7.79	158.39	53.09	62.36	117.5	1(7), 3(1)
15	84.21	152.21	127.63	23.89	18.7	1(8)
16	0.67	2.46	1.27	0.68	53.9	2(8)
33	1.41	21.49	8.58	7.37	86.0	3(8)
34	6.34	6.35	6.35	0.00	0.0	2(8)
35	0.03	0.05	0.04	0.01	18.6	2(8)
36	0.73	3.38	1.82	0.97	53.0	2(8)
37	1.68	3.98	2.61	0.97	37.3	2(8)
38	0.68	2.42	1.75	0.55	31.4	1(2), 3(6)
39	20.10	35.27	27.35	5.97	21.8	3(8)
40	0.17	0.34	0.27	0.05	20.2	2(8)
41	37.06	150.45	80.35	34.90	43.4	1(1), 3(7)
42	6.37	7.20	6.49	0.29	4.4	2(8)
43	0.20	0.72	0.40	0.17	41.8	2(8)
44	4.25	7.51	5.60	1.11	19.8	2(8)
45	22.42	56.19	32.80	10.53	32.1	2(8)
46	2.09	5.26	3.94	1.09	27.7	2(6), 3(2)
47	154.23	211.21	184.31	17.46	9.5	3(8)
48	0.37	0.79	0.50	0.14	28.6	2(8)

[a]sd indicates standard deviation.
[b]CoV indicates coefficient of variation.
[c]Failure mode: 1 = cohesive; 2 = adhesive; 3 = mixed; numbers in parentheses indicate the number of specimens in the sample set that experienced the given mode.

Table 5B. Summary of the T-peel creep-rupture data for Tape System 2

Sample Set No.	Time-to-Failure, hours min	max	mean	sd[a]	CoV[b] %	Failure Mode[c]
17	1.42	19.22	9.75	7.07	72.5	2(5), 3(3)
18	0.01	0.03	0.01	0.01	45.7	2(8)
19	0.03	0.08	0.05	0.02	31.5	2(8)
20	1.54	4.86	3.59	1.15	32.0	2(8)
21	2.31	4.78	3.29	0.74	22.5	2(8)
22	5.81	37.34	23.24	9.09	39.1	1(3), 2(1), 3(4)
23	7.94	33.80	20.82	9.41	45.2	1(6), 2(2)
24	0.43	0.79	0.60	0.13	22.2	2(8)
25	3.04	22.22	7.66	6.96	90.8	2(8)
26	6.47	6.65	6.54	0.07	1.0	2(8)
27	0.22	0.37	0.30	0.05	16.4	2(8)
28	10.15	33.17	22.10	7.33	33.2	2(7), 3(1)
29	2.20	49.77	17.89	19.89	111.2	1(2), 2(4), 3(2)
30	36.39	77.77	54.13	15.51	28.7	1(2), 2(1), 3(5)
31	22.35	34.09	28.19	4.76	16.9	1(8)
32	2.46	6.84	4.06	1.92	47.2	2(8)
49	0.21	0.85	0.37	0.21	57.8	2(8)
50	0.01	0.01	0.01	0.00	35.7	2(8)
51	0.01	0.03	0.02	0.00	24.0	2(8)
52	0.99	5.58	2.34	1.48	63.1	2(8)
53	5.68	92.90	35.99	32.56	90.5	2(8)
54	5.55	39.70	26.34	10.75	40.8	1(2), 2(1), 3(5)
55	526.20	1057.66	695.68	200.33	28.8	1(8)
56	0.38	0.72	0.53	0.12	21.8	2(8)
57	0.46	11.89	5.18	4.46	86.0	2(8)
58	6.39	6.44	6.41	0.02	0.3	2(8)
59	0.06	0.11	0.08	0.02	26.1	2(8)
60	4.61	21.85	14.24	7.13	50.1	2(6), 3(2)
61	20.97	44.75	36.52	7.86	21.5	1(4), 3(4)
62	20.57	58.81	37.51	13.40	35.7	1(2), 2(2), 3(4)
63	2.65	66.71	33.68	30.64	91.0	1(4), 2(4)
64	0.83	2.33	1.30	0.49	37.7	2(8)

[a]sd indicates standard deviation.

[b]CoV indicates coefficient of variation.

[c]Failure mode: 1 = cohesive; 2 = adhesive; 3 = mixed; numbers in parentheses indicate the number of specimens in the sample set that experienced the given mode.

As is evident in Figure 2, the mean times-to-failure of the tape-bonded sample sets were quite variable, ranging from a few minutes (i.e., 0.01 hour) to about 700 hours. Figure 2 provides a basis for comparing the effects of varying both the material and application factors on time-to-failure. As is to be discussed, the main effects observed are associated with tape thickness, primer, and EPDM surface condition. A secondary effect associated with the interaction of high temperature, high pressure, and clean EPDM was also observed.

4.2.1 Material Factors. From an examination of the plot characters in Figure 2, the 'standard' thickness sample sets had, in most cases, greater times-to-failure than the thin sample sets. Simultaneous confidence intervals (details not shown) demonstrated that the 'standard'-thickness sample sets had significantly (95 % level) longer mean times-to-failure than the corresponding thin sample sets for 11 of the 16 application factor combinations. And, the thin sample sets did not have significantly longer times-to-failure in the remaining five cases. That is, the time-to-failure results provided no evidence that thinner tapes should be used. The observation of thick tape being longer lived than thin tape was consistent with past NIST results whereby relatively thick layers of butyl-based liquid adhesive provided longer times-to-failure than did relatively thin liquid-adhesive layers [4].

It may also be seen in examining Figure 2 that, for the combinations of application factors, no trend of time-to-failure behavior as a function of tape system is evident. For 10 of the 16 combinations of application factors, simultaneous confidence intervals showed no significant difference in the times-to-failure of the TS1 and TS2 data sets. Where a significant difference existed, the TS1 sample sets had greater mean time-to-failure in four cases, while the TS2 sample sets had shorter mean time-to-failure in two cases.

Two general conclusions can be drawn from Figure 2 regarding the effect of material factors on the creep-rupture behavior of the two tape systems. First, 'standard' thickness tape provided significantly longer times-to-failure than thinner tape. Second, the two tape systems (i.e., TS1 and TS2) responded in the same manner to the different combinations of application factors. That is, factors that promoted either shorter or longer times-to-failure generally did so for both tape systems.

4.2.2 Application Factors. In considering the application factors, it is of interest to compare in Figure 2 the time-to-failure data for the 16 Phase II sample set combinations with the average time-to-failure for the three sets of liquid-adhesive-bonded specimens from Phase I. Eight of the application factor combinations have lower mean times-to-failure than the average for liquid-adhesive-bonded sample sets. Of these eight application factor combinations, seven sets were unprimed. Moreover, of those seven unprimed sets, five included the contaminated EPDM surface condition. Among the six application factor combinations having the mean times-to-failure greater than the liquid-adhesive-bonded sample sets, five were primed, and five had clean EPDM surfaces. And, also included among the six combinations having the highest mean times-to-failure are the four cases where the EPDM is both primed and cleaned. A corollary to this latter observation is that, within the limits set in the experiment, temperature, pressure, and time-at-temperature did not affect the creep-rupture response of the primed and clean sample sets to the extent that the mean times-to-failure were less than that of the liquid-adhesive-bonded sample sets.

The findings in Figure 2 quantify the importance of both priming and cleaning the EPDM rubber, which is in accord with manufacturers' recommendations for fabrication of tape-bonded seams [2]. In general terms, the data in Figure 2 suggest that, if tape-bonded seams are primed, it is reasonable to expect that they will have creep lifetimes comparable to liquid-adhesive-bonded seams. On the other hand, primed tape-bonded seams having clean EPDM can have longer creep lives than liquid-adhesive-bonded seams. And, it is important to point out, the relatively long creep lifetimes of seams made with primed, clean EPDM are not expected to be adversely affected by application temperature and pressure (within the limits selected for the study), which are factors that are uncontrollable in practice.

It is of interest to note that there was one combination of application factors which produced relatively long times-to-failure even though the specimens were unprimed—this is the fourth combination from the right in Figure 2. Notice that this combination had clean EPDM surfaces, high temperature, high pressure, and long time-at-temperature. Apparently this combination of application factors compensated for the unprimed EPDM, as it was the only combination that included no primer and, yet, had times-to-failure greater than the liquid-adhesive-bonded sample sets. This finding has little practical importance, as achieving this combination of application factors in the field may be impossible. It would seem far simpler to ensure that the EPDM is primed and cleaned during seam fabrication.

The most important results on creep life have been summarized in the above paragraphs. However, additional details can still be learned from Figure 2. Note, for example, that the results for the rightmost two combinations are very similar for sample sets having 'standard' thickness tape. Since the only factor which differs between these combinations is time-at-temperature, this provides evidence that, at least by itself, time-at-temperature does not have much of an effect for 'well-made' specimens (i.e., primed and clean EPDM).

4.3 Discussion of Peel-Strength Data

The mean peel-strength data given in Figure 3 represent four measurements for each of the 64 factor combinations. Tables 6A and 6B provide a summary of these data for the 32 TS1 and 32 TS2 sample sets, respectively. As can be seen in Figure 3, the mean peel strengths ranged from about 0.18 kN/m to 2.3 kN/m (1 lbf/in to 13 lbf/in). Values at the upper end of the range were typical of those previously measured for tape-bonded seams made with primed, clean EPDM [2,3].

Regarding material factors, as evident in Figure 3, the sample sets made with 'standard' thickness tape tended to be stronger than those made with thin tape. And, overall, there was little difference in peel strength between the two tape systems except with primed, clean EPDM. Regarding application factors, priming and cleaning of EPDM surfaces was necessary for high peel strength, while unprimed, contaminated EPDM resulted in low peel strength. Notice in Figure 3 that the four combinations of application factors that had the greatest peel strength were prepared with primed and clean EPDM. In contrast, the four combinations of application factors that had the lowest peel strength were prepared with unprimed, contaminated EPDM. Also, it is interesting to note that the sample sets prepared with unprimed, clean EPDM at high temperature,

Table 6A. Summary of the T-peel strength data for Tape System 1

Sample Set No.	Peel strength, kN/m min	max	mean	sd[a]	Peel Strength, lbf/in min	max	mean	sd[a]	CoV[b] %	Failure Mode[c]
1	1.17	1.31	1.22	0.06	6.7	7.5	7.0	0.36	5.1	3
2	0.34	0.42	0.37	0.04	2.0	2.4	2.1	0.21	9.7	2
3	0.28	0.33	0.30	0.02	1.6	1.9	1.7	0.13	7.8	2
4	0.77	0.84	0.79	0.03	4.4	4.8	4.5	0.18	4.1	2
5	0.82	0.86	0.84	0.02	4.7	4.9	4.8	0.10	2.2	2
6	1.42	1.54	1.48	0.06	8.1	8.8	8.5	0.31	3.7	1
7	1.36	1.38	1.37	0.01	7.8	7.9	7.8	0.07	0.9	3
8	0.58	0.67	0.64	0.04	3.3	3.8	3.6	0.24	6.4	2
9	1.55	1.74	1.63	0.10	8.8	9.9	9.3	0.55	5.9	3
10	0.46	0.53	0.50	0.03	2.6	3.0	2.9	0.17	5.8	2
11	0.35	0.47	0.40	0.05	2.0	2.7	2.3	0.30	13.0	2
12	1.17	1.34	1.22	0.08	6.7	7.7	7.0	0.46	6.5	2
13	1.23	1.46	1.40	0.11	7.0	8.3	8.0	0.64	8.1	2
14	0.95	1.56	1.27	0.30	5.4	8.9	7.3	1.72	23.7	1
15	1.73	1.78	1.75	0.03	9.9	10.2	10.0	0.16	1.6	1
16	1.03	1.65	1.28	0.27	5.9	9.4	7.3	1.53	21.0	2
33	0.70	1.37	1.08	0.29	4.0	7.8	6.2	1.67	26.9	3
34	0.30	0.38	0.35	0.04	1.7	2.2	2.0	0.20	10.1	2
35	0.13	0.30	0.19	0.08	0.7	1.7	1.1	0.43	39.8	2
36	0.72	0.88	0.78	0.07	4.1	5.0	4.4	0.41	9.2	2
37	0.91	1.22	1.09	0.15	5.2	7.0	6.2	0.85	13.6	2
38	0.96	1.50	1.18	0.25	5.5	8.6	6.7	1.44	21.4	1
39	1.14	1.52	1.35	0.18	6.5	8.7	7.7	1.05	13.6	3
40	1.01	1.16	1.09	0.07	5.8	6.6	6.2	0.40	6.4	2
41	0.95	1.71	1.43	0.33	5.4	9.8	8.1	1.91	23.4	3
42	0.47	0.53	0.49	0.03	2.7	3.0	2.8	0.16	5.8	2
43	0.41	0.52	0.47	0.04	2.4	3.0	2.7	0.25	9.2	2
44	1.21	1.66	1.41	0.18	6.9	9.5	8.0	1.05	13.1	2
45	1.48	1.76	1.60	0.14	8.4	10.1	9.2	0.80	8.8	3
46	1.19	1.58	1.45	0.18	6.8	9.0	8.3	1.01	12.2	1
47	1.70	1.87	1.80	0.07	9.7	10.7	10.3	0.40	3.9	3
48	1.03	1.32	1.15	0.12	5.9	7.5	6.6	0.70	10.6	2

[a]sd indicates standard deviation.
[b]CoV indicates coefficient of variation.
[c]Failure mode: 1 = cohesive; 2 = adhesive; 3 = mixed.

Table 6B. Summary of the T-peel strength data for Tape System 2

Sample	Peel strength, kN/m				Peel Strength, lbf/in				CoV[b]	Failure
Set No.	min	max	mean	sd[a]	min	max	mean	sd[a]	%	Mode[c]
17	0.89	0.99	0.94	0.05	5.1	5.6	5.4	0.28	5.1	2
18	0.17	0.20	0.19	0.02	0.9	1.1	1.1	0.09	8.5	2
19	0.20	0.36	0.30	0.07	1.2	2.0	1.7	0.40	23.0	2
20	0.70	0.77	0.74	0.03	4.0	4.4	4.2	0.18	4.3	2
21	0.94	1.42	1.23	0.21	5.4	8.1	7.0	1.21	17.2	2
22	1.69	1.80	1.75	0.05	9.7	10.3	10.0	0.28	2.8	3
23	1.61	1.73	1.69	0.05	9.2	9.9	9.6	0.31	3.2	1
24	1.05	1.27	1.17	0.10	6.0	7.3	6.7	0.59	8.9	2
25	1.12	1.35	1.20	0.11	6.4	7.7	6.8	0.61	8.9	2
26	0.49	0.53	0.50	0.02	2.8	3.0	2.9	0.10	3.4	2
27	0.75	0.81	0.77	0.03	4.3	4.6	4.4	0.16	3.6	2
28	1.00	1.41	1.17	0.17	5.7	8.0	6.7	0.97	14.5	2
29	1.09	1.28	1.19	0.08	6.2	7.3	6.8	0.45	6.6	2
30	2.20	2.45	2.32	0.12	12.5	14.0	13.3	0.71	5.4	3
31	2.05	2.20	2.13	0.06	11.7	12.6	12.1	0.34	2.8	3
32	1.24	1.63	1.40	0.17	7.1	9.3	8.0	0.96	12.0	2
49	0.39	0.66	0.54	0.11	2.2	3.8	3.1	0.64	20.9	2
50	0.16	0.19	0.18	0.01	0.9	1.1	1.0	0.06	6.3	2
51	0.02	0.09	0.07	0.03	0.1	0.5	0.4	0.18	46.7	2
52	0.69	0.77	0.73	0.04	3.9	4.4	4.2	0.23	5.6	2
53	1.60	1.92	1.76	0.13	9.1	10.9	10.1	0.75	7.4	2
54	1.45	1.79	1.59	0.16	8.3	10.2	9.1	0.89	9.8	2
55	2.27	2.38	2.31	0.05	12.9	13.6	13.2	0.29	2.2	1
56	0.95	1.17	1.07	0.10	5.4	6.7	6.1	0.56	9.2	2
57	0.55	0.71	0.63	0.09	3.2	4.1	3.6	0.49	13.7	2
58	0.50	0.58	0.53	0.04	2.9	3.3	3.1	0.20	6.6	2
59	0.23	0.29	0.25	0.02	1.3	1.6	1.5	0.14	9.6	2
60	1.03	1.34	1.12	0.15	5.9	7.7	6.4	0.83	12.9	2
61	1.55	1.91	1.69	0.16	8.8	10.9	9.7	0.89	9.2	3
62	1.97	2.19	2.08	0.09	11.2	12.5	11.9	0.53	4.4	3
63	2.26	2.36	2.30	0.04	12.9	13.5	13.1	0.25	1.9	3
64	1.14	1.42	1.27	0.12	6.5	8.1	7.2	0.67	9.3	2

[a]sd indicates standard deviation.
[b]CoV indicates coefficient of variation.
[c]Failure mode: 1 = cohesive; 2 = adhesive; 3 = mixed.

high pressure, and long time-at-temperature had relatively high strength (fifth combination from the right in Figure 3).

4.4 Failure Mode During Creep-Rupture and Peel-Strength Measurements

Examination of the failure modes in Tables 5A and 5B for the creep-rupture sample sets and Tables 6A and 6B for the peel-strength sample sets shows that the vast majority failed adhesively or in a mixed mode (i.e., some areas of the specimen bond failing cohesively and others adhesively). Specimens prepared without primer or with contaminated EPDM might be expected to fail adhesively. In the Phase II Main Experiment, 75 % of the sample sets were prepared with EPDM that was either unprimed or contaminated, or both. And, it was found that all specimens in sets having both unprimed and contaminated EPDM failed adhesively in the creep-rupture and peel-strength tests.

However, in contrast, only 8 % of the 32 tested sample sets (16 in creep and 16 in peel strength) having primed, clean EPDM failed in a totally cohesive mode. For the creep-rupture measurements, these were Sample Sets Nos. 15, 31, and 55; for the peel-strength measurements, they were Sample Sets Nos. 6, 14, 15, 23, 38, 46, and 55. Note that only two of the seven samples sets (Nos. 15 and 55) that failed cohesively in peel strength also failed cohesively in creep; Sample Set No. 31 failed cohesively in creep, and in a mixed mode in peel. On the other hand, no sample set prepared with primed, clean EPDM failed totally in an adhesive mode. Most of them contained some specimens that failed cohesively and others that failed in a mixed mode (with, in some cases, a few specimens that failed adhesively). In two instances (Sample Sets Nos. 39 and 47), all specimens having cleaned, primed EPDM failed in a mixed mode. The observation that few primed, clean sample sets failed cohesively was in distinct contrast to the findings in Phase I, wherein almost all sample sets failed cohesively* [2,3].

Selected primed specimens, prepared using either clean or contaminated EPDM and which failed adhesively, were examined with light microscopy at x100 magnification to determine the locus of adhesive failure. In the case of the TS1 primed, clean specimens, the failure was between the tape and the primer. The bonds between the clean EPDM and primer (and within the tape) were apparently stronger than those between the tape and primer. In the case of the TS1 primed, contaminated specimens, two loci of failure were evidenced: between the EPDM and the primer, and between the tape and the primer. No trend for one to predominate over the other in relation to the application conditions was observed. In contrast, the loci of failure for almost all TS2 primed specimens, whether clean or contaminated, were between the EPDM and the TS2 primer. Statistical analysis of the creep-rupture data revealed that sample sets failing cohesively tended to have longer times-to-failure than those failing adhesively. Also, sample sets failing in a mixed mode exhibited longer times-to-failure similar to those failing cohesively. The findings of this analysis are implicit in the rank ordering of the times-to-failure given in the plot in Figure 2. The data points for unprimed, contaminated sample sets, which failed adhesively, are found on the left side of the plot; whereas the data points for the primed, clean sample sets, which failed mainly cohesively or in a mixed mode, are situated on the right side of the plot.

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*One TS2 sample set failed adhesively in Phase I, but that failure was attributed to preparing specimens with primer that had reached the end of its shelf life [3].

One question was why the primed, clean sample sets in the Phase II Main Experiment underwent relatively few cohesive failures, while in Phase I such sample sets almost always failed cohesively. A possible reason was that the failure mode was influenced by the high and low application temperatures and pressures (Table 1) used in preparing the Phase II specimens. In Phase I, the specimens were prepared at room temperature, about 23 °C (73 °F), using cleaned, primed EPDM; the application pressure was 0.7 MPa (100 lbf/in^2). That is, none of the specimens in the Phase II Main Experiment were prepared using the same application conditions of Phase I. Thus, additional sets of TS1 and TS2 specimens were prepared using the Phase II materials and the Phase I application conditions. The availability of these sample sets allowed for a comparison of times-to-failure and peel strengths of Phase I and Phase II specimens prepared under identical application conditions.

The comparison between the times-to-failure and peel strengths of the Phase I and Phase II sample sets, made under identical application conditions, is summarized in Table 7. The creep-rupture tests were performed at a load of 9.3 N (2.1 lbf), i.e., the single load used in Phase II. It is evident in Table 7 that the TS2 sample sets performed comparably in Phases I and II. With regard to creep, the range and mean of the times-to-failure were slightly lower in Phase II than in Phase I. Although the mean values were statistically significantly different, no importance was attached to the slight difference. With regard to peel strength, no significant difference was found between the mean values, and the ranges were about the same. In both peel and creep, the failure modes were cohesive. Because the TS2 data for specimens made under identical conditions were similar in Phases I and II, no further comparative testing of TS2 specimens was conducted. These results for TS2 suggested that the application factors such as temperature and pressure may have influenced the failure mode of the TS2 primed, clean sample sets tested in the Phase II Main Experiment (Sections 4.2 and 4.3). Further experimentation would be needed to provide a definitive conclusion.

Table 7. Comparison between Phase I and Phase II times-to-failure and peel strengths

Adh. Syst.	Phase	Time-to-Failure, hours					Peel Strength, kN/m (lbf/in)				
		min	max	mean[a]	CoV[b]	FM[c]	min	max	mean[d]	CoV[b]	FM[c]
TS1	I	39.28	59.06	44.42	14.6	1	1.79 (10.2)	1.82 (10.4)	1.81 (10.4)	0.9	1
TS1	II	4.73	147.0	52.22	132	1,2,3	1.28 (7.30)	1.73 (9.90)	1.55 (8.87)	11.4	1,2,3
TS2	I	66.14	105.1	89.33	17.1	1	2.05 (11.7)	2.42 (13.8)	2.25 (12.8)	6.6	1
TS2	II	51.40	74.15	61.41	12.4	1	2.17 (12.4)	2.32 (13.2)	2.23 (12.7)	3.2	1

[a]Average of seven or eight specimens.
[a]CoV indicates coefficient of variation.
[c]FM indicates failure mode; 1 = cohesive, 2 = adhesive, and 3 = mixed.
[d]Average of four or five specimens.

In contrast to the TS2 results, it is evident in Table 7 that the TS1 sample sets did not perform comparably in Phases I and II. Although the mean times-to-failure of the Phase I and Phase II sample sets (i.e., 44 versus 52 hours) were not significantly different, the time-to-failure ranges were very different. Most notably, for the Phase II set, the range was from 4.7 hours to 147 hours, which resulted in a coefficient of variation (CoV) of 132 %. The Phase I sample set showed a range of 39 hours to 59 hours with a CoV of 14.6 %. Also, for the Phase II sample set, the failure mode was variable—three specimens failed cohesively, three adhesively, and one mixed. All Phase I specimens failed cohesively. Moreover, the Phase II specimens that failed adhesively had a mean time-to-failure of about 5 hours; whereas those that failed cohesively and mixed had a mean time-to-failure of about 100 hours. These observations regarding differences between the TS1 results in Phases I and II suggest that, when comparisons of creep rupture data are made between replicate sample sets, it may be necessary to compare more parameters than mean time-to-failure to judge whether the data are similar.

The mean peel strength of the TS1 Phase II sample set was about 15 percent less (the difference was statistically significant) than that of the Phase I sample set. Although this small difference was not, in itself, considered to be notable, the failure modes for the Phase II peel specimens were cohesive, adhesive, or mixed—as was found for the creep-rupture specimens. Again, this was in contrast with the Phase I specimens that failed cohesively during peel-strength measurements.

From the data and failure modes in Table 7, some difference in behavior between the Phase I and Phase II TS1 sample sets (prepared using the same conditions) was occurring. One hypothesis as to the cause(s) was that the TS1 primer from Phase I used preparing Phase II specimens (Section 3.1) was beyond its shelf life. Thus, a new batch of TS1 primer was obtained, and an additional set of TS1 specimens was prepared using the Phase I application conditions. However, the creep-rupture and peel-strength results from this sample set and those of the TS1 Phase II sample set (Table 7) were about the same. This observation suggested that the primer was not the cause.

Another hypothesis as to the cause of the variability between the TS1 Phase I and Phase II data was that the laboratory application technique had been unknowingly altered so that some TS1 Phase II specimens had failed adhesively. An experiment was needed to investigate the variability of the TS1 results.

The experiment and results are described in Appendix C. In summary, it was found that tape was primarily responsible for the TS1 variability, and little effect due to primer was observed. It was also seen that the TS1 sample sets in the experiment were statistically longer lived than the minimum mean times-to-failure of three sets of well prepared liquid-adhesive-bonded specimens from Phase I.

5. SUMMARY AND CONCLUSIONS

Tape adhesive systems are being used increasingly for preparing seams of EPDM roofing membranes. An industry-government consortium study is underway to develop nonproprietary data on tape-bonded seam performance. In Phase I, the creep-rupture response (time-to-failure) of tape-bonded seam specimens subjected to various peel loads under ambient conditions was compared to that of liquid-adhesive-bonded specimens. This report has described the results of the Phase II research to study the effects of material and application factors on the peel-creep-rupture response and peel strength of tape-bonded seam specimens. Two material factors—tape system and tape thickness—and five application factors—EPDM surface condition, primer, application temperature, application pressure, and time-at-application temperature—were investigated in a statistically designed experiment. Two commercial tape systems were included and the tapes had thicknesses of approximately 0.9 mm (0.035 in) or approximately 0.6 mm (0.025 in). Because the thicker tapes had thicknesses typical of those commercially available at the time of the study, they were designated as having 'standard' thickness. The two levels at which each application factor was examined were chosen to represent, for the most part, the range of commercial practice. Thus, specimens were prepared either primed or unprimed using EPDM that was either clean or contaminated. Application temperatures were low, 5 °C (41 °F), or high, 60 °C (140 °F), and application pressures were low, 0.2 MPa (30 lbf/in^2), or high, 2 MPa (300 lbf/in^2). And, the time at which the specimens remained at the application temperature were either short, about 24 hours, or long, 672-960 hours.

The T-peel strengths and times-to-failure were determined at room temperature. The creep load was 9.3 N (2.1 lbf). To interpret the data, plots of mean time-to-failure and mean peel strength versus the combinations of application factors for each of the four pairs of tape system and tape thickness were analyzed. Comparisons of times-to-failure between the tape-bonded sample sets were made with those of well prepared liquid-adhesive-bonded sample sets from Phase I. In recent years, field experience with liquid-adhesive-bonded seams has been, in most cases, satisfactory. Consequently, the laboratory-measured times-to-failure of well prepared liquid-adhesive-bonded specimens were taken as the benchmark for acceptable creep lifetimes. The main conclusions regarding tape-bonded seams from the Phase II experimentation were that:

- *Primed, clean EPDM provided the longest times-to-failure and highest peel strengths.* These findings were consistent with manufacturers' recommendations for 'good application practice' that require seams be primed and cleaned during fabrication. The findings are important because they quantify such recommendations and emphasize the importance that they be followed.
- *Primed, clean EPDM and 'standard thickness tape' afforded times-to-failure that were statistically significantly higher than minimum mean times-to-failure of well prepared liquid-adhesive-bonded specimens investigated in Phase I.* This result from Phase II reinforces the main conclusion from Phase I; that is, well prepared tape-bonded seam specimens of the type in this study have satisfactory creep lifetimes in that, in most cases, they are comparable to, or greater than, those of well prepared liquid-adhesive-bonded specimens.
- *Application temperatures and application pressures used in the investigation did not affect the times-to-failure of specimens prepared with primed, clean EPDM, that had, as stated, relatively long times-to-failure.* This is important as it indicates that tape-bonded seams can be expected to have satisfactory creep lifetimes when prepared over a routinely encountered

range of application temperatures, i.e., 5 °C to 60 °C (41 °F to 140 °F), and pressures—factors that can be uncontrollable in practice.

- *'Standard' thickness tape provided significantly longer times-to-failure than thinner tape.* The thickness of the 'standard thickness' tapes were typical of those used in practice at the time of the study, and no evidence was obtained that, for the two tape systems, thinner tapes should be used.
- *The two tape systems generally responded similarly to factors that promoted either shorter or longer times-to-failure.*

In addition to these main conclusions, it was found that different batches of tape and primer of one tape system provided seam sample sets having variable times-to-failure. Investigation of the cause indicated that the tape was primarily responsible; no substantial effect due to primer was observed. Investigations on the variability of the tape were beyond the scope of the project. Although variable, sample sets prepared with this tape system had mean times-to-failure that were statistically longer than the minimum mean times-to-failure of three sets of well prepared liquid-adhesive-bonded specimens from Phase I.

6. ACKNOWLEDGMENTS

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APPENDIX A. SPECIMEN PREPARATION

This appendix describes specimen preparation. As indicated in the main text, two material factors (tape system and thickness) and five application factors (EPDM surface condition, primer, application temperature and pressure, and time-at-temperature) were investigated in the Phase II Main Experiment (Table 1). The general specimen preparation conditions and procedures have been previously described [2,4], and were followed in preparing the Phase II specimens.

A1. SPECIMEN MATERIALS AND DIMENSIONS

Two tape systems (TS1 and TS2) were used to prepare T-peel seam specimens having dimensions of 25 mm by 125 mm (1 in by 5 in) with a 75 mm (3 in) length bonded with tape. The tapes were 75 mm (3 in) in width. The EPDM rubber sheet having a nominal thickness of 1.5 mm (0.060 in) was a commercial nonreinforced product amply covered on its surfaces with a talc-like release agent. For each tape system, the tapes were supplied at two thicknesses, designated standard and thin. The thicknesses of the 'standard thickness' tapes were generally 0.9 mm to 1.0 mm (0.035 in to 0.040 in). These tapes were commercial products. The thicknesses of the 'thin' tapes were generally 0.5 mm to 0.6 mm (0.020 in to 0.025 in). These 'thin' tapes were noncommercial products manufactured specifically for the Phase II investigations. In all cases, before a specimen was subjected to either a peel-strength or creep-rupture test, the thickness of the tape was measured using the procedure described in Rossiter et al. [4]. Thickness measurements of the creep-rupture specimens are included Appendix B.

A2. RUBBER SURFACE CONDITION

The surfaces of the EPDM rubber sheets used to prepare the T-peel specimens were designated either clean or contaminated. In the case of the 'clean' surface, the as-received EPDM was first washed with Sparkleen-brand laboratory detergent in tap water, rinsed, and dried overnight or longer. Just before fabrication of the seam specimens, the EPDM surface was further cleaned by wiping with a cloth soaked in heptane. The procedure has been described in Rossiter et al. [4].

In the case of the 'contaminated' surface, the coverage of the release agent on the as-received EPDM appeared to be sufficiently uniform that it could be used directly for specimen preparation. However, because of the ample amount of release agent on the EPDM surfaces, neither the TS1 nor the TS2 tapes would adhere to the as-received EPDM. Thus, some release agent was removed using the following procedure. A strip of 75 mm (3 in) wide masking tape was placed on the bonding area (fig. A1) of a 150 mm by 200 mm (6 in by 8 in) piece of as-received EPDM.* Then, a 4.7 kg brass cylinder with a diameter of 75 mm (3 in) and a length of 119 mm (4.75 in) was slowly (< 5 s) rolled back and forth once across the masking tape. When the masking tape was peeled from the as-received EPDM, some release agent was removed from the EPDM surface. As a result, both tapes could now be bonded to the EPDM surface, which was designated as contaminated.

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*The 25 mm by 125 mm (1 in by 5 in) T-peel specimens were subsequently cut from the sections of specimens prepared using the 150 mm by 200 mm (6 in by 8 in) piece of EPDM.

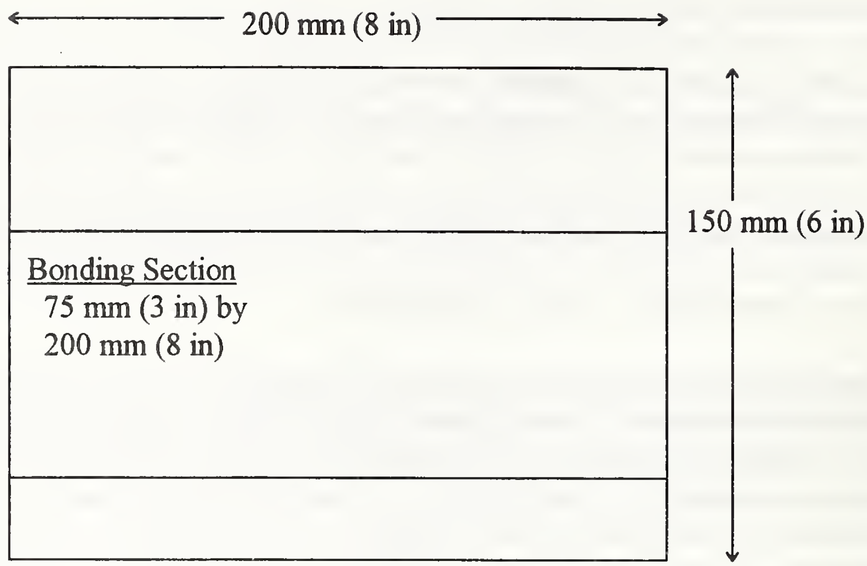

Figure A1. Plan view of a piece of EPDM used in specimen preparation.

The EPDM surface condition, i.e., clean or contaminated, was quantified by the technique described in Martin et al. [5,6]. This technique uses computer-image processing to measure the reflectance of tungsten light from the surfaces of the EPDM rubber strips. Light reflection from the black EPDM surface increases with increasing contamination by the white release-agent particles. Reflectance is quantified according to a grayscale output from the image processor. The grayscale value is zero for black and 255 for a white surface. Forty grayscale measurements were made over the 75 mm by 200 mm (3 in by 8 in) bonding area of the EPDM (fig. A1). Only about 5 percent of the cleaned pieces of EPDM were quantified, as past NIST experience has indicated that the cleaning procedure produces uniform surfaces from specimen to specimen [4]. The average grayscale values of these clean surfaces were in the range of 38-42, with a coefficient of variation of less than 10 percent. This range was similar to those values (i.e., 30-33, and 38) in previous NIST studies [2,4,5]. For contaminated specimens, the average grayscale values of the EPDM were in the range of 130 to 150, with a coefficient of variation of 12 percent or less. Tables B1 and B2 contain the grayscale values for the TS1 and TS2 specimens, respectively, used in the creep-rupture tests. Note in the tables that a nominal value of 40 was assigned for the clean specimens, because it was the mid-range value for those that were measured.

A3. PRIMER

Specimens were designated 'primed' and 'unprimed.' When 'unprimed,' the tape was applied directly to either the clean or contaminated EPDM surface. When 'primed,' the thicknesses of the primer were in accordance with each tape manufacturer's instructions: about 0.07 mm and 0.04 mm (0.0028 in and 0.0014 in) for Tape System 1 and Tape System 2, respectively. To

control the thickness, a drawdown blade technique* with the EPDM held firmly on a vacuum table was used [A1].

A4. TEMPERATURE

A4.1 High Temperature

For the hot temperature application, the EPDM (fig. A1) and tape pieces, 225 mm (9 in) in length, were placed in an oven at 60 °C ± 2 °C (140 °F ± 4 °F) for a minimum of 24 hours. The primer was left at room temperature for safety purposes. A heated vacuum table, set close to the oven, provided a working area to apply the primer and tape to the rubber. Two hot plates were covered with a 250 mm by 300 mm by 6 mm (10 in by 12 in by 0.25 in) aluminum plate on which the vacuum table was placed. The hot plates were heated such that a Type K (chromel-alumel) thermocouple placed between the vacuum table and piece of rubber registered 60 °C ± 3 °C (140 °F ± 5 °F). Additionally, a second aluminum plate with dimensions of 200 mm by 250 mm by 6 mm (8 in by 10 in by 0.25 in) was set on a single hot plate, which was heated such that a Type K thermocouple placed between the plate and a piece of rubber on it read 60 °C ± 3 °C (140 °F ± 5 °F). This plate was used to maintain the temperature of one of the mating pieces of EPDM while the second was being primed.

In preparing a specimen, a preheated piece of EPDM was removed from the oven and set on the vacuum table where it remained for about 3 minutes before application of the tape and primer (if used). When primer was used, the solvent was allowed to evaporate for about 3 minutes before the tape was applied to the primed EPDM. Then the tape/EPDM piece was transferred to the heated aluminum plate where it was kept hot until the mating piece of EPDM was primed. After solvent in the primer was judged to have evaporated from the second piece of primed EPDM (about 3 minutes), the two were mated and immediately transferred to a pneumatic press for pressure application (Section A5).

In cases where the specimen was not primed, the first piece of EPDM was set on the heated vacuum table after removal from the oven. After 3 minutes, preheated tape was applied, and then another piece of EPDM was removed from the oven and mated directly with that covered with the tape. The mated pieces were immediately transferred to the press for pressure application.

A4.2 Low Temperature

For the low temperature application, a top-opening refrigerator with interior dimensions of 1270 mm by 457 mm by 610 mm depth (50 in by 18 in by 24 in depth) provided the cold working area. All materials, i.e., EPDM, tapes, and primers, were set on the bottom of the chamber along with the vacuum table. The temperature of the chamber was set at 5 °C ± 2 °C (41 °F ± 3 °F), and was measured with a Type K thermocouple placed between the vacuum table and a piece of EPDM set on it. The materials were placed in the refrigerator over night before the specimens were prepared. When preparing the specimens, the lid of the refrigerator was open, and work was conducted by leaning into the chamber. Condensation was not visible on the lower walls of

*This technique uses an adjustable knife blade (i.e., the drawdown blade), bar, or rod to spread the adhesive or primer on a substrate [A1]. The thickness is controlled by the distance between the blade edge and the substrate surface.

the chamber, or on any materials, during specimen preparation. It was visible at times on the walls of the chamber near the top opening. The tapes and primers (if used) were applied to pieces of EPDM placed on the vacuum table. Evaporation of primer solvent required about 25 minutes (as judged by pressing on the primed rubber with a finger) before the tape was put in place. After the two pieces of EPDM were mated together, the specimen was immediately transferred to the pneumatic press for pressure application.

A5. PRESSURE

The specimens were pressed together using a pneumatic press as described in Rossiter et al. [2]. Two pressures, designated high and low, were used in the study: 2 MPa (300 lbf/in^2) and 0.2 MPa (30 lbf/in^2), respectively. The time of pressure application was about 10 s. Immediately after pressure application, the specimens were returned to either an oven or refrigerator where they remained for the pre-selected time (Section A6) before conducting the creep-rupture and peel-strength tests.

A6. TIME-AT-TEMPERATURE

'Time-at-temperature' means holding the completed specimen at the preparation temperature for a specified duration. Two times-at-temperature were specified and designated short and long. The 'short' time-at-temperature was between 20 hours and 24 hours; i.e., about over night. After the short time-at-temperature elapsed, the specimens were kept at room temperature until tested. The 'long' time-at-temperature was essentially the period between specimen preparation and testing, and ranged from 672 hours to 960 hours (28 days to 40 days). However, in this latter case, both creep-rupture and peel-strength specimens were kept at room temperature over night before the tests were conducted.

A7. APPENDIX REFERENCE

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APPENDIX B. CREEP-RUPTURE DATA DEVELOPED IN MAIN EXPERIMENT

This Appendix contains the time-to-failure (TTF) data developed in the Phase II Main Experiment. All specimens were tested at a load of 9.3 N (2.1 lbf). The following codes and abbreviations are used in the tables.

Column Number	Information Given in the Column
1	Sample Set Number (Set No.); it corresponds to the set number given in Table 1 of the main text.
2	Replicate Number of the Sample Set (Set Rep); it was included in the table in the event that more than one sample set was tested.
3	Specimen Number (No.); each specimen was assigned a unique number.
4	TS Number (No.); 1 = Tape System 1; 2 = Tape System 2.
5/6	Tape Thickness in millimeters (mm); Tape Thickness in inches (in).
7	Surface Condition (Cond); specimens were either clean or contaminated (cont.).
8	Gray Scale (GS) of the rubber; clean specimens were assigned a value of 40; gray scales of the contaminated specimens were measured.
9	Application Pressure (Press); high = 2 MPa (300 lbf/in^2); low = 0.2 MPa (30 lbf/in^2).
10	Application Temperature (Temp); high = 60 °C (140 °F); low = 5 °C (41 °F).
11	Time-at-Application-Temperature (Time-at-Temp); short = 20 hours to 24 hours; long = 672 hours to 960 hours.
12	Primer; indicates whether the specimen was primed (Yes) or not primed (No).
13	Time-to-Failure (TTF).
14	Failure Mode (FM); indicates whether the predominant mode of failure was cohesive (1), adhesive (2), or a combination of the two (3).

Table B1. Creep-rupture data developed for Tape System 1 in the Main Experiment

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	Tape Thickness in	Surface Cond	Surface GS	Application Press	Application Temp	Time-at-Temp	Primer	TTF hours	FM
1	1	1B63-27	1	0.724	0.029	Cont.	145	High	High	Short	Yes	1.743	3
1	1	1B63-25	1	0.673	0.027	Cont.	145	High	High	Short	Yes	1.928	3
1	1	1B63-26	1	0.676	0.027	Cont.	145	High	High	Short	Yes	2.365	3
1	1	1B63-24	1	0.660	0.026	Cont.	145	High	High	Short	Yes	3.639	3
1	1	1B62-15	1	0.619	0.024	Cont.	149	High	High	Short	Yes	4.266	3
1	1	1B62-20	1	0.667	0.026	Cont.	149	High	High	Short	Yes	4.361	3
1	1	1B63-23	1	0.648	0.026	Cont.	145	High	High	Short	Yes	4.451	3
1	1	1B62-19	1	0.600	0.024	Cont.	149	High	High	Short	Yes	4.946	3
2	1	2B38-36	1	0.613	0.024	Cont.	146	High	Low	Short	No	6.371	2
2	1	2B36-25	1	0.584	0.023	Cont.	137	High	Low	Short	No	6.374	2
2	1	2B37-35	1	0.613	0.024	Cont.	146	High	Low	Short	No	6.381	2
2	1	2B38-40	1	0.597	0.024	Cont.	146	High	Low	Short	No	6.383	2
2	1	2B38-38	1	0.616	0.024	Cont.	146	High	Low	Short	No	6.383	2
2	1	2B38-39	1	0.610	0.024	Cont.	146	High	Low	Short	No	6.384	2
2	1	2B36-27	1	0.625	0.025	Cont.	137	High	Low	Short	No	6.384	2
2	1	2B36-22	1	0.622	0.025	Cont.	137	High	Low	Short	No	6.394	2
3	1	3B54-5	1	0.702	0.028	Cont.	136	Low	High	Short	No	0.049	2
3	1	3B54-6	1	0.676	0.027	Cont.	136	Low	High	Short	No	0.050	2
3	1	3B55-11	1	0.657	0.026	Cont.	139	Low	High	Short	No	0.056	2
3	1	3B55-12	1	0.641	0.025	Cont.	139	Low	High	Short	No	0.058	2
3	1	3B55-8	1	0.651	0.026	Cont.	139	Low	High	Short	No	0.064	2
3	1	3B55-10	1	0.699	0.028	Cont.	139	Low	High	Short	No	0.065	2
3	1	3B54-7	1	0.711	0.028	Cont.	136	Low	High	Short	No	0.068	2
3	1	3B55-9	1	0.679	0.027	Cont.	139	Low	High	Short	No	0.070	2
4	1	4B44-40	1	0.737	0.029	Cont.	147	Low	Low	Short	Yes	7.348	2
4	1	4B39-2	1	0.740	0.029	Cont.	140	Low	Low	Short	Yes	7.689	2
4	1	4B42-24	1	0.714	0.028	Cont.	140	Low	Low	Short	Yes	7.850	2
4	1	4B44-42	1	0.645	0.025	Cont.	147	Low	Low	Short	Yes	8.351	2
4	1	4B39-7	1	0.721	0.028	Cont.	140	Low	Low	Short	Yes	8.526	2
4	1	4B44-37	1	0.711	0.028	Cont.	147	Low	Low	Short	Yes	9.330	2
4	1	4B42-26	1	0.711	0.028	Cont.	140	Low	Low	Short	Yes	9.668	2
4	1	4B42-27	1	0.714	0.028	Cont.	140	Low	Low	Short	Yes	11.959	2
5	1	5B3-5	1	0.603	0.024	Clean	40	High	High	Short	No	0.385	2
5	1	5B3-6	1	0.606	0.024	Clean	40	High	High	Short	No	0.408	2
5	1	5B4-9	1	0.625	0.025	Clean	40	High	High	Short	No	0.443	2
5	1	5B4-10	1	0.613	0.024	Clean	40	High	High	Short	No	0.485	2
5	1	5B5-20	1	0.594	0.023	Clean	40	High	High	Short	No	0.610	2
5	1	5B5-19	1	0.594	0.023	Clean	40	High	High	Short	No	0.616	2
5	1	5B4-8	1	0.619	0.024	Clean	40	High	High	Short	No	0.651	2
5	1	5B5-17	1	0.610	0.024	Clean	40	High	High	Short	No	0.989	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
6	1	6B26-38	1	0.413	0.016	Clean	40	High	Low	Short	Yes	2.756	1
6	1	6B26-41	1	0.676	0.027	Clean	40	High	Low	Short	Yes	3.437	1
6	1	6B24-22	1	0.718	0.028	Clean	40	High	Low	Short	Yes	6.994	2
6	1	6B24-23	1	0.333	0.013	Clean	40	High	Low	Short	Yes	8.754	3
6	1	6B25-30	1	0.714	0.028	Clean	40	High	Low	Short	Yes	9.085	3
6	1	6B25-31	1	0.654	0.026	Clean	40	High	Low	Short	Yes	10.729	3
6	1	6B25-35	1	0.673	0.027	Clean	40	High	Low	Short	Yes	11.144	3
6	1	6B24-24	1	0.664	0.026	Clean	40	High	Low	Short	Yes	11.237	3
7	1	7B11-19	1	0.752	0.030	Clean	40	Low	High	Short	Yes	3.999	2
7	1	7B11-20	1	0.733	0.029	Clean	40	Low	High	Short	Yes	4.528	2
7	1	7B11-15	1	0.727	0.029	Clean	40	Low	High	Short	Yes	5.226	2
7	1	7B11-21	1	0.730	0.029	Clean	40	Low	High	Short	Yes	5.346	2
7	1	7B10-13	1	0.692	0.027	Clean	40	Low	High	Short	Yes	5.663	2
7	1	7B9-1	1	0.702	0.028	Clean	40	Low	High	Short	Yes	7.736	2
7	1	7B9-7	1	0.737	0.029	Clean	40	Low	High	Short	Yes	8.584	3
7	1	7B9-6	1	0.749	0.030	Clean	40	Low	High	Short	Yes	9.938	3
8	1	8B17-21	1	0.538	0.021	Clean	40	Low	Low	Short	No	0.286	2
8	1	8B17-16	1	0.553	0.022	Clean	40	Low	Low	Short	No	0.304	2
8	1	8B16-12	1	0.563	0.022	Clean	40	Low	Low	Short	No	0.338	2
8	1	8B16-14	1	0.573	0.023	Clean	40	Low	Low	Short	No	0.365	2
8	1	8B16-8	1	0.585	0.023	Clean	40	Low	Low	Short	No	0.463	2
8	1	8B15-3	1	0.535	0.021	Clean	40	Low	Low	Short	No	0.493	2
8	1	8B15-2	1	0.533	0.021	Clean	40	Low	Low	Short	No	0.497	2
8	1	8B16-9	1	0.560	0.022	Clean	40	Low	Low	Short	No	0.633	2
9	1	9C61-25	1	0.879	0.035	Cont.	148	High	High	Short	Yes	10.993	1
9	1	9C61-23	1	0.832	0.033	Cont.	148	High	High	Short	Yes	23.023	1
9	1	9C63-39	1	0.994	0.039	Cont.	143	High	High	Short	Yes	23.750	1
9	1	9C63-40	1	0.953	0.038	Cont.	143	High	High	Short	Yes	27.587	1
9	1	9C63-37	1	0.956	0.038	Cont.	143	High	High	Short	Yes	28.513	1
9	1	9C59-12	1	1.019	0.040	Cont.	147	High	High	Short	Yes	38.324	3
9	1	9C59-9	1	1.073	0.042	Cont.	147	High	High	Short	Yes	43.635	3
9	1	9C63-36	1	0.972	0.038	Cont.	143	High	High	Short	Yes	46.276	1
10	1	10C33-19	1	1.016	0.040	Cont.	140	High	Low	Short	No	6.420	2
10	1	10C32-9	1	0.943	0.037	Cont.	141	High	Low	Short	No	6.436	2
10	1	10C31-3	1	1.019	0.040	Cont.	132	High	Low	Short	No	6.440	2
10	1	10C33-16	1	0.991	0.039	Cont.	140	High	Low	Short	No	6.465	2
10	1	10C33-17	1	0.962	0.038	Cont.	140	High	Low	Short	No	6.473	2
10	1	10C31-5	1	1.051	0.041	Cont.	132	High	Low	Short	No	6.484	2
10	1	10C32-10	1	1.026	0.040	Cont.	141	High	Low	Short	No	6.489	2
10	1	10C31-1	1	0.972	0.038	Cont.	132	High	Low	Short	No	6.516	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
11	1	11B54-15	1	1.064	0.042	Cont.	147	Low	High	Short	No	0.080	2
11	1	11B54-16	1	1.032	0.041	Cont.	147	Low	High	Short	No	0.133	2
11	1	11B55-24	1	1.016	0.040	Cont.	140	Low	High	Short	No	0.133	2
11	1	11B55-26	1	1.057	0.042	Cont.	140	Low	High	Short	No	0.170	2
11	1	11B55-25	1	1.108	0.044	Cont.	140	Low	High	Short	No	0.170	2
11	1	11B55-27	1	1.016	0.040	Cont.	140	Low	High	Short	No	0.201	2
11	1	11B54-20	1	1.003	0.040	Cont.	147	Low	High	Short	No	0.241	2
11	1	11B52-5	1	1.016	0.040	Cont.	143	Low	High	Short	No	0.244	2
12	1	12C37-1	1	1.111	0.044	Cont.	150	Low	Low	Short	Yes	6.638	2
12	1	12C39-16	1	1.172	0.046	Cont.	139	Low	Low	Short	Yes	5.972	2
12	1	12C37-2	1	1.111	0.044	Cont.	150	Low	Low	Short	Yes	4.870	2
12	1	12C39-19	1	1.051	0.041	Cont.	139	Low	Low	Short	Yes	7.199	2
12	1	12C37-4	1	1.127	0.044	Cont.	150	Low	Low	Short	Yes	4.022	2
12	1	12C37-7	1	1.108	0.044	Cont.	150	Low	Low	Short	Yes	4.119	2
12	1	12C39-21	1	1.073	0.042	Cont.	139	Low	Low	Short	Yes	9.470	2
12	1	12C40-23	1	1.089	0.043	Cont.	136	Low	Low	Short	Yes	8.659	2
13	1	13C8-13	1	1.019	0.040	Clean	40	High	High	Short	No	1.743	2
13	1	13C8-8	1	1.010	0.040	Clean	40	High	High	Short	No	2.398	2
13	1	13C9-17	1	0.968	0.038	Clean	40	High	High	Short	No	2.655	2
13	1	13C8-12	1	1.003	0.040	Clean	40	High	High	Short	No	2.785	2
13	1	13C7-4	1	1.016	0.040	Clean	40	High	High	Short	No	2.945	2
13	1	13C9-16	1	0.972	0.038	Clean	40	High	High	Short	No	3.181	2
13	1	13C9-21	1	0.956	0.038	Clean	40	High	High	Short	No	3.672	2
13	1	13C7-5	1	0.959	0.038	Clean	40	High	High	Short	No	5.970	2
14	1	14C28-25	1	0.730	0.029	Clean	40	High	Low	Short	Yes	7.794	1
14	1	14C29-30	1	0.794	0.031	Clean	40	High	Low	Short	Yes	11.125	1
14	1	14C29-32	1	0.816	0.032	Clean	40	High	Low	Short	Yes	12.202	1
14	1	14C29-29	1	0.768	0.030	Clean	40	High	Low	Short	Yes	16.531	1
14	1	14C29-33	1	0.708	0.028	Clean	40	High	Low	Short	Yes	20.331	1
14	1	14C28-22	1	0.746	0.029	Clean	40	High	Low	Short	Yes	54.527	1
14	1	14C26-10	1	0.743	0.029	Clean	40	High	Low	Short	Yes	143.854	3
14	1	14C26-12	1	0.829	0.033	Clean	40	High	Low	Short	Yes	158.391	1
15	1	15C15-16	1	1.140	0.045	Clean	40	Low	High	Short	Yes	84.214	1
15	1	15C13-7	1	1.067	0.042	Clean	40	Low	High	Short	Yes	106.377	1
15	1	15C13-5	1	1.118	0.044	Clean	40	Low	High	Short	Yes	114.425	1
15	1	15C15-17	1	1.124	0.044	Clean	40	Low	High	Short	Yes	130.008	1
15	1	15C13-1	1	1.099	0.043	Clean	40	Low	High	Short	Yes	142.477	1
15	1	15C14-14	1	1.051	0.041	Clean	40	Low	High	Short	Yes	144.875	1
15	1	15C14-11	1	1.124	0.044	Clean	40	Low	High	Short	Yes	146.489	1
15	1	15C15-21	1	1.105	0.044	Clean	40	Low	High	Short	Yes	152.213	1

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
16	1	16C24-39	1	0.998	0.039	Clean	40	Low	Low	Short	No	0.668	2
16	1	16C24-38	1	0.993	0.039	Clean	40	Low	Low	Short	No	0.704	2
16	1	16C24-41	1	0.978	0.038	Clean	40	Low	Low	Short	No	0.791	2
16	1	16C24-37	1	0.988	0.039	Clean	40	Low	Low	Short	No	0.884	2
16	1	16C23-32	1	0.990	0.039	Clean	40	Low	Low	Short	No	1.140	2
16	1	16C23-30	1	0.970	0.038	Clean	40	Low	Low	Short	No	1.351	2
16	1	16C23-33	1	0.995	0.039	Clean	40	Low	Low	Short	No	2.150	2
16	1	16C21-17	1	0.968	0.038	Clean	40	Low	Low	Short	No	2.462	2
33	1	33B61-10	1	0.606	0.024	Cont.	144	High	High	Long	Yes	1.406	3
33	1	33B61-13	1	0.597	0.024	Cont.	144	High	High	Long	Yes	1.988	3
33	1	33B61-14	1	0.651	0.026	Cont.	144	High	High	Long	Yes	3.218	3
33	1	33B61-9	1	0.638	0.025	Cont.	144	High	High	Long	Yes	4.904	3
33	1	33B60-7	1	0.619	0.024	Cont.	145	High	High	Long	Yes	6.505	3
33	1	33B60-4	1	0.660	0.026	Cont.	145	High	High	Long	Yes	13.817	3
33	1	33B60-5	1	0.657	0.026	Cont.	145	High	High	Long	Yes	15.297	3
33	1	33B60-3	1	0.673	0.027	Cont.	145	High	High	Long	Yes	21.487	3
34	1	34B33-2	1	0.635	0.025	Cont.	150	High	Low	Long	No	6.342	2
34	1	34B35-19	1	0.654	0.026	Cont.	148	High	Low	Long	No	6.344	2
34	1	34B35-16	1	0.667	0.026	Cont.	148	High	Low	Long	No	6.345	2
34	1	34B34-10	1	0.629	0.025	Cont.	150	High	Low	Long	No	6.345	2
34	1	34B35-15	1	0.641	0.025	Cont.	148	High	Low	Long	No	6.346	2
34	1	34B35-17	1	0.648	0.026	Cont.	148	High	Low	Long	No	6.346	2
34	1	34B33-6	1	0.657	0.026	Cont.	150	High	Low	Long	No	6.347	2
34	1	34B34-13	1	0.632	0.025	Cont.	150	High	Low	Long	No	6.348	2
35	1	35B56-21	1	0.581	0.023	Cont.	144	Low	High	Long	No	0.032	2
35	1	35B59-39	1	0.689	0.027	Cont.	139	Low	High	Long	No	0.033	2
35	1	35B56-19	1	0.660	0.026	Cont.	144	Low	High	Long	No	0.036	2
35	1	35B58-31	1	0.664	0.026	Cont.	144	Low	High	Long	No	0.041	2
35	1	35B56-17	1	0.638	0.025	Cont.	144	Low	High	Long	No	0.044	2
35	1	35B58-29	1	0.619	0.024	Cont.	144	Low	High	Long	No	0.049	2
35	1	35B59-36	1	0.664	0.026	Cont.	139	Low	High	Long	No	0.050	2
35	1	35B59-40	1	0.686	0.027	Cont.	139	Low	High	Long	No	0.051	2
36	1	36B41-20	1	0.737	0.029	Cont.	142	Low	Low	Long	Yes	0.909	2
36	1	36B43-29	1	0.622	0.025	Cont.	146	Low	Low	Long	Yes	3.378	2
36	1	36B43-32	1	0.762	0.030	Cont.	146	Low	Low	Long	Yes	2.152	2
36	1	36B41-21	1	0.749	0.030	Cont.	142	Low	Low	Long	Yes	0.957	2
36	1	36B43-33	1	0.676	0.027	Cont.	146	Low	Low	Long	Yes	2.453	2
36	1	36B40-9	1	0.641	0.025	Cont.	141	Low	Low	Long	Yes	1.386	2
36	1	36B43-34	1	0.765	0.030	Cont.	146	Low	Low	Long	Yes	2.626	2
36	1	36B40-14	1	0.664	0.026	Cont.	141	Low	Low	Long	Yes	0.728	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
37	1	37B46-8	1	0.552	0.022	Clean	40	High	High	Long	No	3.014	2
37	1	37B46-9	1	0.505	0.020	Clean	40	High	High	Long	No	2.754	2
37	1	37B45-1	1	0.514	0.020	Clean	40	High	High	Long	No	3.980	2
37	1	37B47-17	1	0.511	0.020	Clean	40	High	High	Long	No	1.682	2
37	1	37B45-7	1	0.530	0.021	Clean	40	High	High	Long	No	1.815	2
37	1	37B47-15	1	0.514	0.020	Clean	40	High	High	Long	No	3.972	2
37	1	37B45-2	1	0.486	0.019	Clean	40	High	High	Long	No	1.861	2
37	1	37B47-20	1	0.492	0.019	Clean	40	High	High	Long	No	1.803	2
38	1	38B23-16	1	0.513	0.020	Clean	40	High	Low	Long	Yes	0.679	1
38	1	38B23-18	1	0.748	0.029	Clean	40	High	Low	Long	Yes	1.277	1
38	1	38B21-4	1	0.588	0.023	Clean	40	High	Low	Long	Yes	1.721	3
38	1	38B21-1	1	0.392	0.015	Clean	40	High	Low	Long	Yes	1.728	3
38	1	38B21-3	1	0.473	0.019	Clean	40	High	Low	Long	Yes	1.966	3
38	1	38B22-11	1	0.613	0.024	Clean	40	High	Low	Long	Yes	2.045	3
38	1	38B23-20	1	0.603	0.024	Clean	40	High	Low	Long	Yes	2.150	3
38	1	38B23-21	1	0.710	0.028	Clean	40	High	Low	Long	Yes	2.419	3
39	1	39B49-12	1	0.543	0.021	Clean	40	Low	High	Long	Yes	20.097	3
39	1	39B49-8	1	0.603	0.024	Clean	40	Low	High	Long	Yes	21.026	3
39	1	39B50-16	1	0.641	0.025	Clean	40	Low	High	Long	Yes	21.508	3
39	1	39B50-20	1	0.606	0.024	Clean	40	Low	High	Long	Yes	26.359	3
39	1	39B48-1	1	0.600	0.024	Clean	40	Low	High	Long	Yes	29.438	3
39	1	39B49-13	1	0.629	0.025	Clean	40	Low	High	Long	Yes	31.940	3
39	1	39B50-19	1	0.648	0.026	Clean	40	Low	High	Long	Yes	33.130	3
39	1	39B49-9	1	0.660	0.026	Clean	40	Low	High	Long	Yes	35.272	3
40	1	40B19-31	1	0.565	0.022	Clean	40	Low	Low	Long	No	0.171	2
40	1	40B19-30	1	0.595	0.023	Clean	40	Low	Low	Long	No	0.225	2
40	1	40B20-39	1	0.580	0.023	Clean	40	Low	Low	Long	No	0.226	2
40	1	40B20-36	1	0.603	0.024	Clean	40	Low	Low	Long	No	0.277	2
40	1	40B18-24	1	0.585	0.023	Clean	40	Low	Low	Long	No	0.292	2
40	1	40B20-37	1	0.580	0.023	Clean	40	Low	Low	Long	No	0.294	2
40	1	40B20-41	1	0.568	0.022	Clean	40	Low	Low	Long	No	0.302	2
40	1	40B19-35	1	0.603	0.024	Clean	40	Low	Low	Long	No	0.336	2
41	1	41C60-18	1	0.911	0.036	Cont.	145	High	High	Long	Yes	37.062	3
41	1	41C60-19	1	0.911	0.036	Cont.	145	High	High	Long	Yes	54.797	3
41	1	41C60-17	1	0.822	0.032	Cont.	145	High	High	Long	Yes	60.790	3
41	1	41C62-30	1	0.978	0.039	Cont.	144	High	High	Long	Yes	71.906	3
41	1	41C60-21	1	0.873	0.034	Cont.	145	High	High	Long	Yes	74.698	3
41	1	41C62-31	1	1.003	0.040	Cont.	144	High	High	Long	Yes	90.433	3
41	1	41C62-32	1	0.949	0.037	Cont.	144	High	High	Long	Yes	102.70	3
41	1	41C58-7	1	0.959	0.038	Cont.	142	High	High	Long	Yes	150.45	3

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
42	1	42C36-39	1	1.019	0.040	Cont.	144	High	Low	Long	No	6.372	2
42	1	42C36-38	1	1.019	0.040	Cont.	144	High	Low	Long	No	6.381	2
42	1	42C34-23	1	0.987	0.039	Cont.	144	High	Low	Long	No	6.383	2
42	1	42C34-24	1	0.981	0.039	Cont.	144	High	Low	Long	No	6.389	2
42	1	42C36-36	1	1.019	0.040	Cont.	144	High	Low	Long	No	6.390	2
42	1	42C35-33	1	1.022	0.040	Cont.	143	High	Low	Long	No	6.399	2
42	1	42C36-42	1	1.041	0.041	Cont.	144	High	Low	Long	No	6.428	2
42	1	42C35-32	1	1.029	0.041	Cont.	143	High	Low	Long	No	7.197	2
43	1	43B53-8	1	0.948	0.037	Cont.	135	Low	High	Long	No	0.201	2
43	1	43B53-9	1	0.927	0.037	Cont.	135	Low	High	Long	No	0.237	2
43	1	43B56-29	1	0.930	0.037	Cont.	134	Low	High	Long	No	0.314	2
43	1	43B56-30	1	1.026	0.040	Cont.	134	Low	High	Long	No	0.357	2
43	1	43B57-42	1	0.924	0.036	Cont.	146	Low	High	Long	No	0.378	2
43	1	43B53-13	1	0.876	0.035	Cont.	135	Low	High	Long	No	0.482	2
43	1	43B57-39	1	0.918	0.036	Cont.	146	Low	High	Long	No	0.482	2
43	1	43B56-35	1	0.953	0.038	Cont.	134	Low	High	Long	No	0.722	2
44	1	44C42-42	1	1.054	0.042	Cont.	145	Low	Low	Long	Yes	4.811	2
44	1	44C41-32	1	1.146	0.045	Cont.	140	Low	Low	Long	Yes	5.526	2
44	1	44C38-12	1	1.187	0.047	Cont.	146	Low	Low	Long	Yes	7.508	2
44	1	44C38-8	1	1.130	0.045	Cont.	146	Low	Low	Long	Yes	5.448	2
44	1	44C42-38	1	1.095	0.043	Cont.	145	Low	Low	Long	Yes	6.411	2
44	1	44C41-33	1	1.127	0.044	Cont.	140	Low	Low	Long	Yes	4.466	2
44	1	44C41-35	1	1.159	0.046	Cont.	140	Low	Low	Long	Yes	6.359	2
44	1	44C42-37	1	1.111	0.044	Cont.	145	Low	Low	Long	Yes	4.248	2
45	1	45C45-17	1	0.905	0.036	Clean	40	High	High	Long	No	26.528	2
45	1	45C45-20	1	0.892	0.035	Clean	40	High	High	Long	No	27.665	2
45	1	45C43-2	1	1.003	0.040	Clean	40	High	High	Long	No	22.424	2
45	1	45C44-12	1	0.937	0.037	Clean	40	High	High	Long	No	36.261	2
45	1	45C45-21	1	0.949	0.037	Clean	40	High	High	Long	No	32.331	2
45	1	45C43-3	1	0.899	0.035	Clean	40	High	High	Long	No	34.510	2
45	1	45C44-9	1	0.933	0.037	Clean	40	High	High	Long	No	56.189	2
45	1	45C45-16	1	0.908	0.036	Clean	40	High	High	Long	No	26.455	2
46	1	46C25-7	1	0.832	0.033	Clean	40	High	Low	Long	Yes	2.087	2
46	1	46C25-4	1	0.819	0.032	Clean	40	High	Low	Long	Yes	2.834	2
46	1	46C30-39	1	0.791	0.031	Clean	40	High	Low	Long	Yes	3.679	2
46	1	46C27-19	1	0.794	0.031	Clean	40	High	Low	Long	Yes	3.991	2
46	1	46C30-42	1	0.819	0.032	Clean	40	High	Low	Long	Yes	4.178	2
46	1	46C30-36	1	0.797	0.031	Clean	40	High	Low	Long	Yes	4.236	3
46	1	46C30-38	1	0.879	0.035	Clean	40	High	Low	Long	Yes	5.258	3
46	1	46C25-5	1	0.778	0.031	Clean	40	High	Low	Long	Yes	5.262	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
47	1	47C49-7	1	1.045	0.041	Clean	40	Low	High	Long	Yes	154.23	3
47	1	47C50-10	1	1.010	0.040	Clean	40	Low	High	Long	Yes	168.70	3
47	1	47C50-12	1	1.022	0.040	Clean	40	Low	High	Long	Yes	182.45	3
47	1	47C51-19	1	1.057	0.042	Clean	40	Low	High	Long	Yes	182.55	3
47	1	47C51-20	1	0.997	0.039	Clean	40	Low	High	Long	Yes	184.67	3
47	1	47C50-8	1	0.924	0.036	Clean	40	Low	High	Long	Yes	192.78	3
47	1	47C50-13	1	0.988	0.039	Clean	40	Low	High	Long	Yes	197.85	3
47	1	47C51-21	1	1.035	0.041	Clean	40	Low	High	Long	Yes	211.21	3
48	1	48C22-22	1	0.918	0.036	Clean	40	Low	Low	Long	No	0.371	2
48	1	48C22-25	1	0.940	0.037	Clean	40	Low	Low	Long	No	0.401	2
48	1	48C22-23	1	0.955	0.038	Clean	40	Low	Low	Long	No	0.417	2
48	1	48C19-1	1	0.900	0.035	Clean	40	Low	Low	Long	No	0.424	2
48	1	48C22-27	1	0.940	0.037	Clean	40	Low	Low	Long	No	0.456	2
48	1	48C22-26	1	0.910	0.036	Clean	40	Low	Low	Long	No	0.488	2
48	1	48C22-24	1	0.933	0.037	Clean	40	Low	Low	Long	No	0.638	2
48	1	48C20-13	1	0.918	0.036	Clean	40	Low	Low	Long	No	0.786	2

Table B2. Creep-rupture data developed for Tape System 2 in the Main Experiment

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	Tape Thickness in	Surface Cond	Surface GS	Application Press	Application Temp	Time-at-Temp	Primer	TTF hours	FM
17	1	17E1-27	2	0.559	0.022	Cont.	137	High	High	Short	Yes	1.421	2
17	1	17E3-39	2	0.556	0.022	Cont.	145	High	High	Short	Yes	3.222	2
17	1	17E53-17	2	0.549	0.022	Cont.	132	High	High	Short	Yes	4.450	2
17	1	17E53-15	2	0.530	0.021	Cont.	132	High	High	Short	Yes	7.008	2
17	1	17E53-16	2	0.572	0.023	Cont.	132	High	High	Short	Yes	8.339	2
17	1	17E53-18	2	0.530	0.021	Cont.	132	High	High	Short	Yes	16.786	3
17	1	17E53-19	2	0.549	0.022	Cont.	132	High	High	Short	Yes	17.574	3
17	1	17E53-20	2	0.549	0.022	Cont.	132	High	High	Short	Yes	19.219	3
18	1	18E35-18	2	0.514	0.020	Cont.	148	High	Low	Short	No	0.009	2
18	1	18E33-4	2	0.552	0.022	Cont.	149	High	Low	Short	No	0.010	2
18	1	18E35-15	2	0.518	0.020	Cont.	148	High	Low	Short	No	0.011	2
18	1	18E35-19	2	0.552	0.022	Cont.	148	High	Low	Short	No	0.012	2
18	1	18E35-17	2	0.521	0.021	Cont.	148	High	Low	Short	No	0.014	2
18	1	18E33-5	2	0.514	0.020	Cont.	149	High	Low	Short	No	0.015	2
18	1	18E33-3	2	0.470	0.019	Cont.	149	High	Low	Short	No	0.015	2
18	1	18E37-30	2	0.512	0.020	Cont.	144	High	Low	Short	No	0.030	2
19	1	19E45-1	2	0.470	0.019	Cont.	139	Low	High	Short	No	0.035	2
19	1	19E45-3	2	0.527	0.021	Cont.	139	Low	High	Short	No	0.036	2
19	1	19E49-30	2	0.486	0.019	Cont.	131	Low	High	Short	No	0.039	2
19	1	19E48-22	2	0.425	0.017	Cont.	135	Low	High	Short	No	0.048	2
19	1	19E48-23	2	0.511	0.020	Cont.	135	Low	High	Short	No	0.054	2
19	1	19E48-28	2	0.492	0.019	Cont.	135	Low	High	Short	No	0.064	2
19	1	19E48-27	2	0.521	0.021	Cont.	135	Low	High	Short	No	0.075	2
19	1	19E49-34	2	0.429	0.017	Cont.	131	Low	High	Short	No	0.076	2
20	1	20E32-38	2	0.508	0.020	Cont.	135	Low	Low	Short	Yes	1.541	2
20	1	20E32-39	2	0.537	0.021	Cont.	135	Low	Low	Short	Yes	2.744	2
20	1	20E28-11	2	0.530	0.021	Cont.	140	Low	Low	Short	Yes	2.841	2
20	1	20E30-28	2	0.533	0.021	Cont.	139	Low	Low	Short	Yes	3.602	2
20	1	20E32-40	2	0.518	0.020	Cont.	135	Low	Low	Short	Yes	3.971	2
20	1	20E28-8	2	0.495	0.020	Cont.	140	Low	Low	Short	Yes	4.463	2
20	1	20E32-36	2	0.483	0.019	Cont.	135	Low	Low	Short	Yes	4.704	2
20	1	20E28-13	2	0.479	0.019	Cont.	140	Low	Low	Short	Yes	4.864	2
21	1	21E5-21	2	0.556	0.022	Clean	40	High	High	Short	No	2.314	2
21	1	21E3-2	2	0.572	0.023	Clean	40	High	High	Short	No	2.848	2
21	1	21E5-20	2	0.530	0.021	Clean	40	High	High	Short	No	2.899	2
21	1	21E3-6	2	0.575	0.023	Clean	40	High	High	Short	No	3.047	2
21	1	21E5-18	2	0.556	0.022	Clean	40	High	High	Short	No	3.179	2
21	1	21E4-9	2	0.552	0.022	Clean	40	High	High	Short	No	3.517	2
21	1	21E5-19	2	0.572	0.023	Clean	40	High	High	Short	No	3.694	2
21	1	21E5-16	2	0.543	0.021	Clean	40	High	High	Short	No	4.783	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
22	1	22E23-15	2	0.498	0.020	Clean	40	High	Low	Short	Yes	5.808	2
22	1	22E22-13	2	0.524	0.021	Clean	40	High	Low	Short	Yes	19.168	3
22	1	22E22-12	2	0.505	0.020	Clean	40	High	Low	Short	Yes	21.317	3
22	1	22E22-11	2	0.521	0.021	Clean	40	High	Low	Short	Yes	22.088	3
22	1	22E24-23	2	0.508	0.020	Clean	40	High	Low	Short	Yes	23.525	1
22	1	22E22-10	2	0.521	0.021	Clean	40	High	Low	Short	Yes	27.515	1
22	1	22E23-21	2	0.495	0.020	Clean	40	High	Low	Short	Yes	29.182	1
22	1	22E24-26	2	0.473	0.019	Clean	40	High	Low	Short	Yes	37.343	3
23	1	23E10-11	2	0.546	0.022	Clean	40	Low	High	Short	Yes	7.941	2
23	1	23E10-10	2	0.530	0.021	Clean	40	Low	High	Short	Yes	8.239	2
23	1	23E11-20	2	0.562	0.022	Clean	40	Low	High	Short	Yes	15.200	1
23	1	23E11-17	2	0.508	0.020	Clean	40	Low	High	Short	Yes	22.729	1
23	1	23E9-3	2	0.527	0.021	Clean	40	Low	High	Short	Yes	25.156	1
23	1	23E9-6	2	0.524	0.021	Clean	40	Low	High	Short	Yes	25.462	1
23	1	23E11-16	2	0.549	0.022	Clean	40	Low	High	Short	Yes	28.034	1
23	1	23E9-1	2	0.514	0.020	Clean	40	Low	High	Short	Yes	33.800	1
24	1	24E18-25	2	0.533	0.021	Clean	40	Low	Low	Short	No	0.435	2
24	1	24E19-35	2	0.463	0.018	Clean	40	Low	Low	Short	No	0.457	2
24	1	24E19-33	2	0.488	0.019	Clean	40	Low	Low	Short	No	0.477	2
24	1	24E18-28	2	0.515	0.020	Clean	40	Low	Low	Short	No	0.571	2
24	1	24E18-24	2	0.513	0.020	Clean	40	Low	Low	Short	No	0.653	2
24	1	24E16-8	2	0.490	0.019	Clean	40	Low	Low	Short	No	0.658	2
24	1	24E18-22	2	0.550	0.022	Clean	40	Low	Low	Short	No	0.738	2
24	1	24E19-29	2	0.513	0.020	Clean	40	Low	Low	Short	No	0.785	2
25	1	25H53-25	2	0.975	0.038	Cont.	149	High	High	Short	Yes	3.043	2
25	1	25H50-5	2	0.949	0.037	Cont.	148	High	High	Short	Yes	3.153	2
25	1	25H50-3	2	0.927	0.037	Cont.	148	High	High	Short	Yes	3.735	2
25	1	25H53-26	2	0.949	0.037	Cont.	149	High	High	Short	Yes	3.808	2
25	1	25H53-28	2	0.937	0.037	Cont.	149	High	High	Short	Yes	4.780	2
25	1	25H50-1	2	0.965	0.038	Cont.	148	High	High	Short	Yes	6.233	2
25	1	25H54-34	2	0.953	0.038	Cont.	145	High	High	Short	Yes	14.334	2
25	1	25H54-29	2	0.994	0.039	Cont.	145	High	High	Short	Yes	22.218	2
26	1	26H33-9	2	0.921	0.036	Cont.	140	High	Low	Short	No	6.475	2
26	1	26H35-28	2	0.892	0.035	Cont.	149	High	Low	Short	No	6.492	2
26	1	26H33-11	2	0.879	0.035	Cont.	140	High	Low	Short	No	6.496	2
26	1	26H32-7	2	0.883	0.035	Cont.	144	High	Low	Short	No	6.504	2
26	1	26H35-22	2	0.879	0.035	Cont.	149	High	Low	Short	No	6.518	2
26	1	26H32-2	2	0.908	0.036	Cont.	144	High	Low	Short	No	6.598	2
26	1	26H35-25	2	0.826	0.033	Cont.	149	High	Low	Short	No	6.606	2
26	1	26H35-23	2	0.857	0.034	Cont.	149	High	Low	Short	No	6.649	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
27	1	27H45-9	2	0.924	0.036	Cont.	135	Low	High	Short	No	0.222	2
27	1	27H49-41	2	0.914	0.036	Cont.	133	Low	High	Short	No	0.268	2
27	1	27H45-8	2	0.889	0.035	Cont.	135	Low	High	Short	No	0.275	2
27	1	27H46-16	2	0.918	0.036	Cont.	136	Low	High	Short	No	0.298	2
27	1	27H46-15	2	0.883	0.035	Cont.	136	Low	High	Short	No	0.308	2
27	1	27H49-40	2	0.876	0.035	Cont.	133	Low	High	Short	No	0.343	2
27	1	27H46-18	2	0.899	0.035	Cont.	136	Low	High	Short	No	0.351	2
27	1	27H49-37	2	0.927	0.037	Cont.	133	Low	High	Short	No	0.373	2
28	1	28H26-3	2	0.892	0.035	Cont.	146	Low	Low	Short	Yes	10.150	2
28	1	28H27-9	2	0.940	0.037	Cont.	137	Low	Low	Short	Yes	17.279	2
28	1	28H26-1	2	0.899	0.035	Cont.	146	Low	Low	Short	Yes	17.569	2
28	1	28H26-5	2	0.962	0.038	Cont.	146	Low	Low	Short	Yes	21.064	2
28	1	28H27-10	2	0.914	0.036	Cont.	137	Low	Low	Short	Yes	21.982	2
28	1	28H29-23	2	0.902	0.036	Cont.	144	Low	Low	Short	Yes	27.257	2
28	1	28H29-26	2	0.949	0.037	Cont.	144	Low	Low	Short	Yes	28.363	3
28	1	28H29-24	2	0.870	0.034	Cont.	144	Low	Low	Short	Yes	33.172	2
29	1	29H3-12	2	0.965	0.038	Clean	40	High	High	Short	No	2.200	2
29	1	29H4-18	2	0.927	0.037	Clean	40	High	High	Short	No	3.421	2
29	1	29H3-13	2	0.927	0.037	Clean	40	High	High	Short	No	3.867	2
29	1	29H4-15	2	0.946	0.037	Clean	40	High	High	Short	No	4.332	2
29	1	29H2-4	2	1.000	0.039	Clean	40	High	High	Short	No	9.445	3
29	1	29H2-1	2	0.952	0.037	Clean	40	High	High	Short	No	23.672	3
29	1	29H2-2	2	0.978	0.039	Clean	40	High	High	Short	No	46.380	1
29	1	29H2-7	2	0.927	0.037	Clean	40	High	High	Short	No	49.770	1
30	1	30H25-41	2	0.848	0.033	Clean	40	High	Low	Short	Yes	36.392	2
30	1	30H21-11	2	0.946	0.037	Clean	40	High	Low	Short	Yes	38.536	3
30	1	30H25-42	2	0.876	0.035	Clean	40	High	Low	Short	Yes	44.695	3
30	1	30H25-38	2	0.883	0.035	Clean	40	High	Low	Short	Yes	47.728	1
30	1	30H21-10	2	0.889	0.035	Clean	40	High	Low	Short	Yes	51.359	3
30	1	30H20-5	2	0.911	0.036	Clean	40	High	Low	Short	Yes	64.404	3
30	1	30H21-13	2	0.927	0.037	Clean	40	High	Low	Short	Yes	72.140	3
30	1	30H20-3	2	0.737	0.029	Clean	40	High	Low	Short	Yes	77.768	1
31	1	31H8-6	2	0.962	0.038	Clean	40	Low	High	Short	Yes	22.348	1
31	1	31H9-12	2	1.013	0.040	Clean	40	Low	High	Short	Yes	23.656	1
31	1	31H8-4	2	0.943	0.037	Clean	40	Low	High	Short	Yes	24.527	1
31	1	31H10-20	2	0.956	0.038	Clean	40	Low	High	Short	Yes	26.062	1
31	1	31H9-10	2	0.994	0.039	Clean	40	Low	High	Short	Yes	28.439	1
31	1	31H10-18	2	0.927	0.037	Clean	40	Low	High	Short	Yes	32.514	1
31	1	31H10-15	2	0.879	0.035	Clean	40	Low	High	Short	Yes	33.888	1
31	1	31H10-21	2	0.965	0.038	Clean	40	Low	High	Short	Yes	34.092	1

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
32	1	32H18-31	2	1.015	0.040	Clean	40	Low	Low	Short	No	2.460	2
32	1	32H18-35	2	1.003	0.039	Clean	40	Low	Low	Short	No	2.462	2
32	1	32H18-32	2	0.960	0.038	Clean	40	Low	Low	Short	No	2.542	2
32	1	32H18-33	2	0.997	0.039	Clean	40	Low	Low	Short	No	2.659	2
32	1	32H18-30	2	0.977	0.038	Clean	40	Low	Low	Short	No	3.622	2
32	1	32H19-39	2	0.957	0.038	Clean	40	Low	Low	Short	No	5.132	2
32	1	32H19-38	2	0.970	0.038	Clean	40	Low	Low	Short	No	6.765	2
32	1	32H19-36	2	0.973	0.038	Clean	40	Low	Low	Short	No	6.837	2
49	1	49E2-32	2	0.521	0.021	Cont.	149	High	High	Long	Yes	0.214	2
49	1	49E51-4	2	0.549	0.022	Cont.	141	High	High	Long	Yes	0.240	2
49	1	49E2-35	2	0.562	0.022	Cont.	149	High	High	Long	Yes	0.246	2
49	1	49E51-1	2	0.524	0.021	Cont.	141	High	High	Long	Yes	0.248	2
49	1	49E2-33	2	0.533	0.021	Cont.	149	High	High	Long	Yes	0.327	2
49	1	49E51-6	2	0.556	0.022	Cont.	141	High	High	Long	Yes	0.348	2
49	1	49E51-7	2	0.514	0.020	Cont.	141	High	High	Long	Yes	0.493	2
49	1	49E52-13	2	0.530	0.021	Cont.	131	High	High	Long	Yes	0.854	2
50	1	50E36-26	2	0.498	0.020	Cont.	149	High	Low	Long	No	0.007	2
50	1	50E36-25	2	0.498	0.020	Cont.	149	High	Low	Long	No	0.007	2
50	1	50E34-9	2	0.495	0.020	Cont.	143	High	Low	Long	No	0.007	2
50	1	50E34-10	2	0.508	0.020	Cont.	143	High	Low	Long	No	0.007	2
50	1	50E38-39	2	0.514	0.020	Cont.	146	High	Low	Long	No	0.010	2
50	1	50E38-42	2	0.509	0.020	Cont.	146	High	Low	Long	No	0.010	2
50	1	50E38-38	2	0.514	0.020	Cont.	146	High	Low	Long	No	0.015	2
50	1	50E38-36	2	0.527	0.021	Cont.	146	High	Low	Long	No	0.015	2
51	1	51E46-11	2	0.435	0.017	Cont.	136	Low	High	Long	No	0.011	2
51	1	51E47-17	2	0.410	0.016	Cont.	141	Low	High	Long	No	0.017	2
51	1	51E47-19	2	0.467	0.018	Cont.	141	Low	High	Long	No	0.017	2
51	1	51E50-41	2	0.422	0.017	Cont.	132	Low	High	Long	No	0.021	2
51	1	51E47-15	2	0.391	0.015	Cont.	141	Low	High	Long	No	0.023	2
51	1	51E46-9	2	0.467	0.018	Cont.	136	Low	High	Long	No	0.024	2
51	1	51E50-37	2	0.425	0.017	Cont.	132	Low	High	Long	No	0.024	2
51	1	51E47-16	2	0.467	0.018	Cont.	141	Low	High	Long	No	0.025	2
52	1	52E29-19	2	0.524	0.021	Cont.	143	Low	Low	Long	Yes	0.995	2
52	1	52E31-30	2	0.518	0.020	Cont.	139	Low	Low	Long	Yes	1.362	2
52	1	52E29-17	2	0.533	0.021	Cont.	143	Low	Low	Long	Yes	1.372	2
52	1	52E29-20	2	0.505	0.020	Cont.	143	Low	Low	Long	Yes	1.932	2
52	1	52E27-2	2	0.568	0.022	Cont.	134	Low	Low	Long	Yes	1.936	2
52	1	52E31-33	2	0.486	0.019	Cont.	139	Low	Low	Long	Yes	2.327	2
52	1	52E31-35	2	0.559	0.022	Cont.	139	Low	Low	Long	Yes	3.192	2
52	1	52E27-7	2	0.549	0.022	Cont.	134	Low	Low	Long	Yes	5.577	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
53	1	53E41-19	2	0.410	0.016	Clean	40	High	High	Long	No	7.670	2
53	1	53E39-6	2	0.441	0.017	Clean	40	High	High	Long	No	77.999	2
53	1	53E39-7	2	0.403	0.016	Clean	40	High	High	Long	No	29.888	2
53	1	53E41-20	2	0.495	0.020	Clean	40	High	High	Long	No	5.678	2
53	1	53E39-4	2	0.473	0.019	Clean	40	High	High	Long	No	92.899	2
53	1	53E40-14	2	0.445	0.018	Clean	40	High	High	Long	No	11.218	2
53	1	53E40-11	2	0.460	0.018	Clean	40	High	High	Long	No	31.991	2
53	1	53E40-12	2	0.489	0.019	Clean	40	High	High	Long	No	30.611	2
54	1	54E26-40	2	0.521	0.021	Clean	40	High	Low	Long	Yes	5.550	2
54	1	54E25-35	2	0.543	0.021	Clean	40	High	Low	Long	Yes	17.628	3
54	1	54E21-1	2	0.527	0.021	Clean	40	High	Low	Long	Yes	25.262	3
54	1	54E21-5	2	0.543	0.021	Clean	40	High	Low	Long	Yes	27.161	3
54	1	54E26-42	2	0.505	0.020	Clean	40	High	Low	Long	Yes	27.569	3
54	1	54E21-6	2	0.552	0.022	Clean	40	High	Low	Long	Yes	32.389	3
54	1	54E21-3	2	0.552	0.022	Clean	40	High	Low	Long	Yes	35.455	1
54	1	54E21-2	2	0.489	0.019	Clean	40	High	Low	Long	Yes	39.701	1
55	1	55E44-16	2	0.505	0.020	Clean	40	Low	High	Long	Yes	526.20	1
55	1	55E43-8	2	0.455	0.018	Clean	40	Low	High	Long	Yes	537.15	1
55	1	55E44-17	2	0.445	0.018	Clean	40	Low	High	Long	Yes	539.48	1
55	1	55E43-11	2	0.467	0.018	Clean	40	Low	High	Long	Yes	587.00	1
55	1	55E42-5	2	0.422	0.017	Clean	40	Low	High	Long	Yes	687.38	1
55	1	55E44-20	2	0.473	0.019	Clean	40	Low	High	Long	Yes	690.46	1
55	1	55E42-2	2	0.419	0.017	Clean	40	Low	High	Long	Yes	940.1	1
55	1	55E44-19	2	0.495	0.020	Clean	40	Low	High	Long	Yes	1057.6	1
56	1	56E20-37	2	0.518	0.020	Clean	40	Low	Low	Long	No	0.376	2
56	1	56E20-39	2	0.528	0.021	Clean	40	Low	Low	Long	No	0.428	2
56	1	56E17-16	2	0.508	0.020	Clean	40	Low	Low	Long	No	0.447	2
56	1	56E20-38	2	0.513	0.020	Clean	40	Low	Low	Long	No	0.496	2
56	1	56E20-36	2	0.495	0.019	Clean	40	Low	Low	Long	No	0.571	2
56	1	56E15-7	2	0.513	0.020	Clean	40	Low	Low	Long	No	0.595	2
56	1	56E15-4	2	0.530	0.021	Clean	40	Low	Low	Long	No	0.626	2
56	1	56E15-2	2	0.528	0.021	Clean	40	Low	Low	Long	No	0.722	2
57	1	57H52-18	2	0.937	0.037	Cont.	149	High	High	Long	Yes	0.465	2
57	1	57H51-10	2	0.930	0.037	Cont.	140	High	High	Long	Yes	1.421	2
57	1	57H51-11	2	0.965	0.038	Cont.	140	High	High	Long	Yes	1.426	2
57	1	57H52-19	2	0.908	0.036	Cont.	149	High	High	Long	Yes	1.856	2
57	1	57H55-37	2	0.937	0.037	Cont.	150	High	High	Long	Yes	6.804	2
57	1	57H51-12	2	0.984	0.039	Cont.	140	High	High	Long	Yes	7.450	2
57	1	57H52-15	2	0.886	0.035	Cont.	149	High	High	Long	Yes	10.152	2
57	1	57H51-8	2	0.924	0.036	Cont.	140	High	High	Long	Yes	11.887	2

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	in	Surface Cond	GS	Application Press	Temp	Time-at-Temp	Primer	TTF hours	FM
58	1	58H34-18	2	0.978	0.039	Cont.	145	High	Low	Long	No	6.392	2
58	1	58H36-31	2	0.933	0.037	Cont.	143	High	Low	Long	No	6.395	2
58	1	58H34-17	2	0.978	0.039	Cont.	145	High	Low	Long	No	6.396	2
58	1	58H37-39	2	0.860	0.034	Cont.	143	High	Low	Long	No	6.401	2
58	1	58H37-40	2	0.908	0.036	Cont.	143	High	Low	Long	No	6.418	2
58	1	58H37-38	2	0.918	0.036	Cont.	143	High	Low	Long	No	6.425	2
58	1	58H37-36	2	0.956	0.038	Cont.	143	High	Low	Long	No	6.427	2
58	1	58H36-29	2	0.930	0.037	Cont.	143	High	Low	Long	No	6.441	2
59	1	59H44-4	2	0.848	0.033	Cont.	140	Low	High	Long	No	0.056	2
59	1	59H47-22	2	0.781	0.031	Cont.	137	Low	High	Long	No	0.062	2
59	1	59H44-3	2	0.870	0.034	Cont.	140	Low	High	Long	No	0.070	2
59	1	59H47-23	2	0.889	0.035	Cont.	137	Low	High	Long	No	0.071	2
59	1	59H44-2	2	0.873	0.034	Cont.	140	Low	High	Long	No	0.078	2
59	1	59H47-27	2	0.845	0.033	Cont.	137	Low	High	Long	No	0.100	2
59	1	59H48-34	2	0.838	0.033	Cont.	139	Low	High	Long	No	0.106	2
59	1	59H48-35	2	0.819	0.032	Cont.	139	Low	High	Long	No	0.112	2
60	1	60H30-31	2	0.984	0.039	Cont.	137	Low	Low	Long	Yes	4.611	2
60	1	60H28-20	2	0.892	0.035	Cont.	133	Low	Low	Long	Yes	4.796	2
60	1	60H28-16	2	0.930	0.037	Cont.	133	Low	Low	Long	Yes	11.184	2
60	1	60H31-36	2	0.870	0.034	Cont.	137	Low	Low	Long	Yes	11.964	2
60	1	60H31-40	2	0.956	0.038	Cont.	137	Low	Low	Long	Yes	17.617	2
60	1	60H31-37	2	0.895	0.035	Cont.	137	Low	Low	Long	Yes	20.612	3
60	1	60H30-34	2	0.975	0.038	Cont.	137	Low	Low	Long	Yes	21.297	2
60	1	60H31-38	2	0.946	0.037	Cont.	137	Low	Low	Long	Yes	21.855	3
61	1	61H40-19	2	0.797	0.031	Clean	40	High	High	Long	No	36.351	3
61	1	61H39-11	2	0.819	0.032	Clean	40	High	High	Long	No	36.447	3
61	1	61H39-12	2	0.870	0.034	Clean	40	High	High	Long	No	44.751	1
61	1	61H40-20	2	0.819	0.032	Clean	40	High	High	Long	No	43.312	1
61	1	61H40-21	2	0.832	0.033	Clean	40	High	High	Long	No	20.969	1
61	1	61H38-6	2	0.832	0.033	Clean	40	High	High	Long	No	43.343	1
61	1	61H38-4	2	0.864	0.034	Clean	40	High	High	Long	No	31.027	1
61	1	61H39-13	2	0.876	0.035	Clean	40	High	High	Long	No	35.945	1
62	1	62H22-20	2	0.895	0.035	Clean	40	High	Low	Long	Yes	20.571	2
62	1	62H22-19	2	0.822	0.032	Clean	40	High	Low	Long	Yes	24.905	2
62	1	62H22-18	2	0.870	0.034	Clean	40	High	Low	Long	Yes	31.276	3
62	1	62H24-31	2	0.902	0.036	Clean	40	High	Low	Long	Yes	33.420	1
62	1	62H24-32	2	0.866	0.034	Clean	40	High	Low	Long	Yes	35.454	1
62	1	62H22-21	2	0.933	0.037	Clean	40	High	Low	Long	Yes	41.260	3
62	1	62H24-29	2	0.902	0.036	Clean	40	High	Low	Long	Yes	54.360	3
62	1	62H23-22	2	0.914	0.036	Clean	40	High	Low	Long	Yes	58.811	3

Set No.	Set Rep	Specimen No.	TS No.	Tape Thickness mm	Tape Thickness in	Surface Cond	Surface GS	Application Press	Application Temp	Time-at-Temp	Primer	TTF hours	FM
63	1	63H42-9	2	0.841	0.033	Clean	40	Low	High	Long	Yes	2.648	2
63	1	63H42-8	2	0.832	0.033	Clean	40	Low	High	Long	Yes	4.444	2
63	1	63H42-12	2	0.838	0.033	Clean	40	Low	High	Long	Yes	5.193	2
63	1	63H42-7	2	0.832	0.033	Clean	40	Low	High	Long	Yes	8.887	2
63	1	63H41-11	2	0.800	0.032	Clean	40	Low	High	Long	Yes	53.690	1
63	1	63H41-5	2	0.835	0.033	Clean	40	Low	High	Long	Yes	61.962	1
63	1	63H41-6	2	0.873	0.034	Clean	40	Low	High	Long	Yes	65.883	1
63	1	63H41-10	2	0.810	0.032	Clean	40	Low	High	Long	Yes	66.707	1
64	1	64H16-18	2	0.880	0.035	Clean	40	Low	Low	Long	No	0.832	2
64	1	64H17-22	2	0.915	0.036	Clean	40	Low	Low	Long	No	0.903	2
64	1	64H16-19	2	0.920	0.036	Clean	40	Low	Low	Long	No	0.953	2
64	1	64H16-17	2	0.910	0.036	Clean	40	Low	Low	Long	No	1.151	2
64	1	64H17-26	2	0.940	0.037	Clean	40	Low	Low	Long	No	1.242	2
64	1	64H17-27	2	0.943	0.037	Clean	40	Low	Low	Long	No	1.375	2
64	1	64H14-3	2	0.920	0.036	Clean	40	Low	Low	Long	No	1.615	2
64	1	64H14-6	2	0.945	0.037	Clean	40	Low	Low	Long	No	2.326	2

APPENDIX C. EXPERIMENT TO INVESTIGATE TS1 VARIABILITY

As indicated in the main text (Section 4.4), variability in creep-rupture results was found among Tape System 1 (TS1) sample sets prepared in Phases I and II of this industry-government consortium study. To investigate the cause(s) of this variability, a full factorial (3 by 2) experiment using three TS1 tapes and two TS1 primers was designed. The materials are listed in Table C1. Six sample sets were prepared (i.e., T1P1, T1P2, T2P1, T2P2, T3P1, and T3P2). Note that these sets include replicate sets of the specimens that were used in Phase I (i.e., T1P1) and Phase II (i.e., T2P1) of the study. Tape 3 and primer 2 were obtained specifically for use in the investigations of the TS1 variability. In all cases, the primer was well stirred before application. Creep-rupture and peel-strength measurements were conducted after the specimens were a minimum of 28 days old. The creep load was 9.3 N (2.1 lbf).

Table C1. Description of TS1 tapes and primers used in the investigation of TS1 variability

Tape			Primer		
Number	Design.[a]	Description	Number	Design.[a]	Description
Tape 1	T1	First tape in the study: • its age was about 22 months. • it was the Phase I tape.	Primer 1	P1	First primer in the study: • its age was about 22 months. • it was the Phase I and Phase II primer.
Tape 2	T2	Second tape in the study: • its age was about 6 months. • it was the Phase II tape.	Primer 2	P2	Second primer in the study: • its age was about 2 months. • it was obtained to be used in the Phase II investigations of the TS1 variability.
Tape 3	T3	Third tape in the study: • its age was about 1 month. • it was obtained to be used in investigations of the TS1 variability.			

[a]Design. indicates designation.

The results of the creep-rupture and peel-strength tests are summarized in Figures C1 and C2, respectively. The error bars represent one standard deviation; the letters above the error bars represent the failure mode (A = adhesive; C = cohesive; M = mixed). Note that Figure C1 has seven bars, because the T2P1 data set is divided into two subsets—one for specimens that failed adhesively (T2P1-A) and the other for those that failed in a mixed mode (T2P1-M).

C1. CREEP-RUPTURE RESULTS

Examination of Figure C1 provides evidence that the TS1 tape, and not the TS1 primer, was primarily responsible for the variability between the TS1 Phase I and Phase II data sets discussed in Section 4.4. Observe in Figure C1 that the times-to-failure vary among the three tapes. In particular, the T3P1 and T3P2 sample sets had mean times-to-failure that were slightly less than 300 hours, which was about a factor of six greater than the mean time-to-failure (about 50 hours) of the

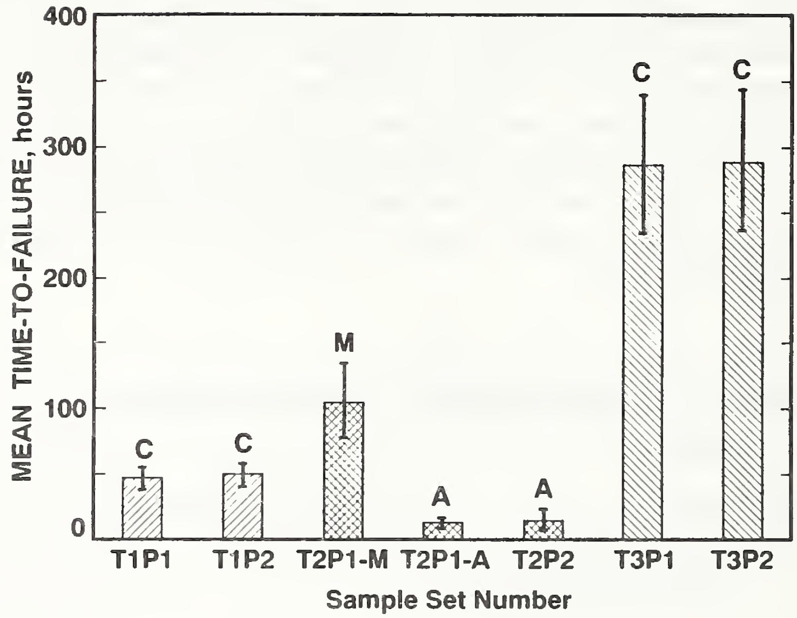

Figure C1. Mean times-to-failure of the sample sets prepared to examine TS1 tape variability. (T1, T2, and T3 indicate the three tapes, and P1and P2 indicate the two primers; the failure modes are: C = cohesive, A = adhesive, and M = mixed cohesive/adhesive. In the case of T2P1, some specimens failed adhesively and some in a mixed mode; a distinction between the two groups is shown by the –M and –A after the T2P1 sample set number.)

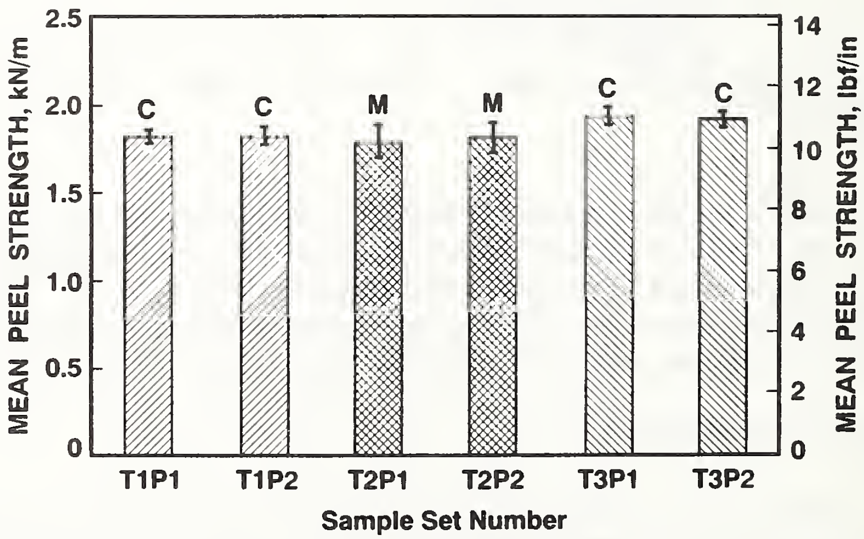

Figure C2. Mean peel strength of the sample sets prepared to examine TS1 tape variability. (T1, T2, and T3 indicate the three tapes, and P1and P2 indicate the two primers; the failure modes are: C = cohesive and M = mixed cohesive/adhesive).

T1P1 and T1P2 sample sets. Moreover, the T2 specimens that failed adhesively (T2P1-A and T2P2) had similar mean times-to-failure of about 12 hours to 14 hours; the difference was not statistically significant. On the other hand, note also in Figure C1 that, for the three pairs of sample sets made with the two primers, the mean times-to-failure were not statistically different within the pair (when the failure modes were the same). That is, no substantial effect due to primer was observed.

The mean times-to-failure (about 50 hours) of the T1P1 and T1P2 sample sets were not statistically significantly different from that obtained for the TS1 sample set (about 44 hours) in Phase I (Table 7). As just noted, the creep-rupture tests of the T1P1 specimen set was a repeat of the Phase I test at 9.3 N (2.1 lbf) using Tape System 1. This finding suggested that the TS1 Phase I data were reproducible, even using tape and primer that were almost 2 years old. Additionally, the finding implied that the laboratory application technique had not been unknowingly altered—at least to the point that the TS1 Phase I results could not be reproduced.

C2. PEEL-STRENGTH RESULTS

It is evident in Figure C2 that little difference was observed between the mean peel-strengths of the six sample sets. For the T1, T2, and T3 sets (ignoring the primer), the mean peel strengths were 1.82 kN/m, 1.79 kN/m, and 1.93 kN/m (10.4 lbf/in, 10.2 lbf/in, and 11.0 lbf/in), respectively. These values were about the same as that found in the Phase I tests (Table 7). However, although the mean strengths were similar for specimens made with the three tapes and two primers, the failure modes were not the same in all six cases. The T1P1/T1P2 and T3P1/T3P2 specimens failed cohesively; whereas the T2P1/T2P2 specimens failed in a mixed mode. This again implied a difference in behavior due to tape and not primer.

C3. TAPE VARIABILITY

A full investigation of the reason(s) why the tape was primarily responsible for the variability between the TS1 Phase I and Phase II data sets was beyond the scope of the project. However, load-elongation tests on the three tape (T1, T2, and T3) were conducted, and mean values of tensile modulus at 300 % elongation (longitudinal direction) are given in Figure C3. The error bars in the plot represent one standard deviation of the mean. The mean values (six measurements) are 19 kPa, 32 kPa, and 30 kPa (2.8 lbf/in^2, 4.6 lbf/in^2, and 4.4 lbf/in^2), respectively. Although the differences were statistically significant, no practical significance was attached to these small differences. The limited data suggest that differences in mechanical properties of the three tapes were not responsible for the variability in creep-rupture and peel-strength between the sample sets made with the three tapes.

C4. COMPARISON OF THE TS1 PHASE II SPECIMENS WITH LIQUID-ADHESIVE-BONDED-SPECIMENS

As indicated in the introduction, a main objective of the joint research program is to compare the creep-rupture performance of tape-bonded and liquid-adhesive-bonded EPDM seams. Consistent with this objective, a comparison may be made between the creep-rupture results of Phase I liquid-adhesive-bonded (LA) specimens with the Phase II TS1 specimens prepared when investigating the

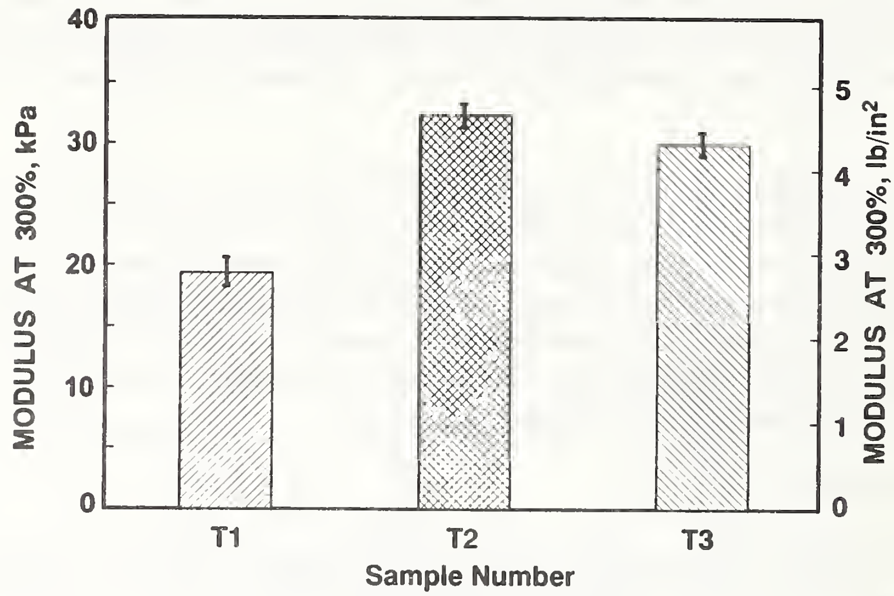

Figure C3. Tape modulus (longitudinal direction) at 300 % elongation. (T1, T2, and T3 indicate the three tapes.)

TS1 variability. The point of comparison is made for sample sets having the shortest mean times-to-failure under the 9.3 N (2.1 lbf) load.

In this regard, in Phase I, the mean times-to-failure for the three sets of liquid-adhesive-bonded specimens (LA Replicate Set Nos. 3-5) with the shortest times-to-failure were 7.0 hours, 6.8 hours, and 8.8 hours (fig. 1) [3]. In Phase II, sample sets T2P1-A and T2P2 had the shortest times-to-failure of those prepared for the TS1 variability investigations (fig. C1). The values were about 12 hours and 14 hours, respectively. Although the five sample sets in question had times-to-failure similar to each other, the Phase II TS1 sets were statistically longer lived than the Phase I LA sample sets.

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